

GEARTECH Report 2038-1

Design Audit of the Wind Turbine Company
Gearbox for the WTC EMD-1 Wind Turbine

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GEARTECH

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TOWNSEND MT 59644

DISCLAIMER

This report may contain certain recommendations for increasing load capacity and improving reliability of the subject gear drive. The recommendations are general guidelines that are for the sole purpose of showing what can be achieved. They must not be construed as specific design recommendations. The manufacturer is solely responsible for the design of the gear drive, and GEARTECH accepts no liability for the design.

This report is a design audit only. The recommendations do not guarantee reliable gearbox performance. Gear manufacturers must follow comprehensive procedures for quality assurance, inspections, and tests to ensure design objectives are achieved. Furthermore, independent inspectors should audit all aspects of manufacture.

Abstract

This report is a design audit of the Wind Turbine Company (WTC) gearbox for the WTC EMD-1 wind turbine.

| <u>Table of Contents</u> | <u>Page</u> |
|---|-------------|
| Conclusions | 5 |
| Recommendations | 7 |
| Summary Tables. | 8 |
| Discussion | 10 |
| Audit Basis. | 10 |
| Gear Hertzian Fatigue Life. | 10 |
| Gear Bending Fatigue Life. | 10 |
| Gear Tribology- Probability of Wear. | 11 |
| Gear Tribology- Probability of Scuffing | 11 |
| Bearing Fatigue L10 Life | 11 |
| Bearing Fatigue L10aa and L1aa Life | 11 |
| Spur versus Helical Gears. | 12 |
| Gear Tooth Rating | 12 |
| Gear Tooth Metallurgy | 12 |
| Lubrication | 14 |
| Recommended Tests. | 14 |
| Applicable Documents | 15 |
| Appendix A – Load Spectrum. | 16-21 |
| Appendix B – Gear Rating | 22-58 |
| Appendix C – Bearing Rating | 59-62 |

Conclusions

1. All gears meet the required Hertzian life $L_{REQD} \geq 132,520$ hours except the LS sun pinion, which has a calculated life of 43,800 hours. The inadequate Hertzian life is primarily caused by the low number of teeth (only 17).
2. All gears meet the required bending fatigue life $L_{REQD} \geq 132,520$ hours.
3. Both gearsets have a high probability of wear.
4. Both gearsets have a low probability of scuffing.
5. Both planet bearings meet GEARTECH guidelines for required life for planet bearings of $L_{10} \geq 140,000$ hours.
6. Both planet bearings do not meet GEARTECH guidelines for $L_{1aa} = L_{REQD} \geq 132,520$ hours. The relatively low viscosity of the lubricant gives a low adjustment factor a_{SKF} and inadequate L_{10aa} and L_{1aa} rated lives.
7. Inertial forces were not considered in this analysis. However, they may be significant for the HS planet bearings.
8. All bearing fits should be tight, or adequate means provided to prevent spinning of inner and outer rings.
9. It will be challenging to achieve a quiet gearbox with spur gears in the HS gearset. In addition to low contact ratio, spur gears are totally dependent on the accuracy of gear tooth profiles, and excessive wear on profiles causes noisy gears. The probability of wear is very high. Furthermore, the gearbox has an integral wet brake, which will contaminate the lubricant with wear debris. Low viscosity lubricant contaminated with brake debris is likely to promote micropitting. Dynamic loads caused by spacing errors may lead to noisy gears or gear failure.
10. Tip diameters of the LS sun, HS sun, and HS planet are smaller than recommended. This results in less contact ratio than necessary and may increase noise level.
11. WTC drawings specify ISO 6336-5 grade ME metallurgical quality for the sun and planet gears. However, ISO 6336-5 is not comprehensive and must be supplemented to adequately control metallurgical quality.
12. WTC drawings for the annulus gears specify through hardened, shaper-cut gear teeth, and relatively low gear tooth accuracy. This processing gives rough, soft gear tooth surfaces that are likely to promote wear and generate noise. The relatively soft surfaces are vulnerable to trapping contaminants. Hard particles embedded in annulus gears cause polishing on mating planet gears. This degrades gear accuracy and generates wear debris. It is especially damaging to spur gears.
13. Wind turbine gearboxes require a lubricant with at least ISO 320 viscosity. The specified lubricant (Mobilfluid 424) has only ISO 55 viscosity, causing a high risk of micropitting. The viscosity-index improver may degrade under the high shear rates attained in gear teeth and bearings. Furthermore, WTC drawings do not specify surface roughness for gear teeth. Therefore, gear tooth surfaces may be rough, and the risk of micropitting increased.

14. Wear debris from the wet brake may contaminate the lubricant, cause polishing wear on planet gears, promote micropitting, and shorten the fatigue life of gears and bearings.

Recommendations

1. The LS pinion should have at least 20 teeth to achieve a good balance between pitting resistance, bending strength, and scuffing resistance.
2. All bearing fits should be tight, or adequate means provided to prevent spinning of inner and outer rings. Planet bearing outer rings should have at least R6 fit with the planet gears. WTC drawings for the gearbox should be reviewed by the bearing manufacturer before using the proposed bearings, cages, and fits. See GEARTECH DOC:010924-WTC-2 for further recommendations.
3. Recommendations given in GEARTECH DOC:010925-WTC-3 for tip diameters should be followed.
4. WTC should show profile charts on the engineering drawings that specify profile modification. See GEARTECH DOC:011003-WTC-5 for recommended profile and helix charts.
5. The LS annulus should be changed to a two-piece construction to allow gear tooth grinding. The design of the HS and LS annulus gears should be changed to specify either carburized or nitrided heat treatment. If carburized, gears should be ground after heat treatment. If nitrided, gears should be ground or shaved before heat treatment.
6. Recommendations given in GEARTECH DOC:011002-WTC-4 for specifications and quality procedures for achieving adequate metallurgical quality should be followed.
7. WTC drawings should specify surface roughness for gear teeth to reduce the risk of micropitting.
8. Sound emission testing should be a first priority. If the operating sound level is unacceptable, there is no point in further testing, and redesign is necessary.
9. After sound emission testing, full-load tests should be conducted to determine micropitting resistance.
10. If sound level is acceptable, and micropitting does not occur, endurance load tests should be conducted to determine if gears and bearings have adequate fatigue life. The endurance load must not be too high. Otherwise, gear tooth profile and lead modifications will be inadequate, and tip-to-root interference or edge contact may occur.

Summary Tables

Gear lives, gear tribology, and bearing lives are reported in Tables 1 through 6. Detail calculations that support data shown in Tables 1 through 6 are contained in Appendices A, B, and C.

| Table 1- Gear Hertzian Fatigue Life (hours) | | |
|--|------------------------------|--------------------------|
| Gear | Hertzian Stress (psi) | Hertzian Life (h) |
| LS Sun | 169,040 | 43,800 |
| LS Planet | 169,040 | 379,000 |
| HS Sun | 116,088 | 4.61E06 |
| HS Planet | 116,088 | 4.01E07 |

| Table 2- Gear Bending Fatigue Life (hours) | | |
|---|-----------------------------|-------------------------|
| Gear | Bending Stress (psi) | Bending Life (h) |
| LS Sun | 28,142 | 1.63E09 |
| LS Planet | 28,374 | 1.05E07 |
| HS Sun | 16,088 | 6.90E15 |
| HS Planet | 15,717 | 1.98E12 |

| Table 3- Gear Tribology- Probability of Wear (%) | | | |
|---|-----------------------------|------------------------------------|--------------------------------|
| Gearset | Film Thickness (μin) | Specific Film Thickness (λ) | Probability of Wear (%) |
| LS | 2.2 | 0.078 | >95 |
| HS | 8.4 | 0.297 | 87 |

| Table 4- Gear Tribology- Probability of Scuffing (%) | | | |
|---|------------------------------------|--------------------------------|------------------------------------|
| Gearset | Max. Specific Sliding Ratio | Max. Contact Temp. (°F) | Probability of Scuffing (%) |
| LS | -1.3745 | 288 | <5 |
| HS | -0.9789 | 310 | <5 |

| Table 5- Bearing Fatigue L10 Life (hours) | | | | | | |
|--|-----------------|----------------------|-------------------------------|--|----------------------------------|-------------------------------------|
| Shaft / Brg. | Brg. No. | Speed n (rpm) | Dynamic Capacity C (N) | Fatigue Limit Load P_u (N) | Equiv. Dynamic Load P (N) | L_{10} Life (h) |
| LS Planet | 24134 | 69.75 | 1,070,000 | 170,000 | 151,644 | 161,000 |
| HS Planet | 22314E | 541.1 | 345,000 | 45,000 | 24,842 | 198,300 |

| Table 6- Bearing Fatigue L10aa and L1aa Life (hours) | | | | | | | |
|---|----------------------------------|----------------------------|--------------------------------------|-----------------------------|-------------------------|---------------------------------------|--------------------------------------|
| Shaft / Brg. | Kappa κ | η_c | $\eta_c * P_u / P$ | a_{SKF} | a_1 | L_{10aa} Life (h) | L_{1aa} Life (h) |
| LS Planet | 0.16 | 0.5 | 0.56 | 0.14 | 0.21 | 22,540 | 4,733 |
| HS Planet | 0.56 | 0.5 | 0.91 | 0.80 | 0.21 | 158,600 | 33,300 |

Notes:

1. Stresses shown in Tables 1 and 2 correspond to rated power of 500 kW.
2. Equivalent dynamic load P shown in Table 5 corresponds to an effective power of 430.43 kW (see Appendix B for calculation of equivalent load).

Discussion

Audit Basis

Calculations are based on geometry, material, heat treatment, accuracy, and quality specified on WTC engineering drawings [6]. Lists of drawings are given in *Applicable Documents*.

Loads used in calculations are based on the WTC load spectrum for rotor torque shown in Appendix A. Baseline load is 160,654 Nm rotor torque at 29.72 rpm corresponding to 500 kW rotor power. The load spectrum includes 2.3631E08 revolutions of the rotor shaft, which corresponds to a required operating life of 132,520 hours.

Lubricant properties are based on the WTC specified Mobilfluid 424, a mineral gear oil with ISO 55 viscosity. Cleanliness is based on $\beta_{10} \geq 200$ filtration. Lubricant properties for bearing life calculations are as follows:

$\theta_{oil} = 70^\circ\text{C}$ (sump operating temperature)

$\theta_M = 85^\circ\text{C}$ (inner ring and roller temperature)

$\nu = 13.5 \text{ mm}^2/\text{s}$ (kinematic viscosity of Mobilfluid 424 at θ_M)

$\eta_c = 0.5$ (SKF contamination factor for normal conditions)

Lubricant properties for gear tribology calculations are as follows:

$\theta_M = 85^\circ\text{C}$ (gear tooth temperature)

$\theta_S = 250^\circ\text{C}$ (oil scuffing temperature)

$\mu_0 = 10.5 \text{ cP}$ (absolute viscosity of Mobilfluid 424 at θ_M)

$\alpha = 1.44 \times 10^{-8} \text{ m}^2/\text{N}$ (pressure-viscosity coefficient of Mobilfluid 424 at θ_M)

Gear Hertzian Fatigue Life

Table 1 shows gear Hertzian fatigue life calculated with the AGMA218 computer program [2] using Miner's Rule for combining loads given in the WTC load spectrum. AGMA218 calculates Hertzian fatigue life in accordance with ANSI/AGMA 2001-C95 [3]. All gears meet the required life $L_{REQD} \geq 132,520$ hours except the LS sun pinion, which has a calculated life of 43,800 hours.

Gear Bending Fatigue Life

Table 2 shows gear bending fatigue life calculated with the AGMA218 computer program [2] using Miner's Rule for combining loads given in the WTC load spectrum. AGMA218 calculates bending fatigue life in accordance with ANSI/AGMA 2001-C95 [3]. All gears meet the required life $L_{REQD} \geq 132,520$ hours.

Gear Tribology- Probability of Wear

Table 3 shows wear probability calculated with the SCORING+ computer program [4] using the maximum load in the WTC load spectrum. SCORING+ calculates probability of wear in accordance with Annex A of ANSI/AGMA 2001-C95 [3]. Both gearsets have a high probability of wear.

Gear Tribology- Probability of Scuffing

Table 4 shows scuffing probability calculated with the SCORING+ computer program [4] using the maximum load in the WTC load spectrum. SCORING+ calculates scuffing probability in accordance with Annex A of ANSI/AGMA 2001-C95 [3]. Both gearsets have a low probability of scuffing.

Bearing Fatigue L10 Life

Table 5 shows planet bearing life calculated in accordance with DIN ISO 281 [5] using Miner's Rule for combining loads given in the WTC load spectrum. L10 life represents 10% probability of failure with all adjustment factors for reliability, material, and lubrication set equal to unity (1.0). Miner's Rule analysis gave an effective power of 430.43 kW. Both planet bearings meet GEARTECH guidelines for required life for planet bearings of $L_{10} \geq 140,000$ hours. However, as shown below, L10aa and L1aa lives are inadequate.

Bearing Fatigue L10aa and L1aa Life

Table 6 shows L10aa and L1aa life calculated using the SKF [5] new life method for adjusted rating life where:

$$L_{naa} = a_1 * a_{SKF} * L_{10}$$

$$L_{10} = (16667/n) * (C/P)^p \quad (p = 10/3 \text{ for roller bearings})$$

L_{10aa} = adjusted rating life according to new life theory for 10% probability of failure (hours)

L_{1aa} = adjusted rating life according to new life theory for 1% probability of failure (hours)

$a_1 = 1.0$ (for 10% failure probability)

$a_1 = 0.21$ (for 1% failure probability)

a_{SKF} = life adjustment factor based on new life theory (from Diagram 5 [5] as a function of viscosity ratio κ and $\eta_c * P_u/P$)

$\kappa = v/v_1$ (viscosity ratio)

v = actual viscosity at operating temperature (mm^2/s)

v_1 = viscosity required for adequate lubrication (mm^2/s)

$\eta_c = 0.5$ (contamination factor for normal conditions)

n = speed (rpm)

C = Basic dynamic capacity (N)

P_u = Fatigue load limit (N)

P = Equivalent dynamic load at effective power of 430.43 kW (N)

Table 6 shows both planet bearings do not meet the required life of $L_{REQD} \geq 132,520$ hours. The relatively low viscosity of the lubricant gives a low adjustment factor a_{SKF} and inadequate L_{10aa} and L_{1aa} rated lives. GEARTECH guidelines are $L_{1aa} = L_{REQD} \geq 132,520$ hours.

Inertial forces were not considered in this analysis. However, they may be significant for the HS planet bearings. They reduce bearing life and may cause failure of the bearing cage. All bearing fits should be tight, or adequate means provided to prevent spinning of inner and outer rings. Planet bearing outer rings should have at least R6 fit with the planet gears. WTC drawings for the gearbox should be reviewed by the bearing manufacturer before using the proposed bearings, cages, and fits. See GEARTECH DOC:010924-WTC-2 [1] for further recommendations.

Spur versus Helical Gears

Spur gears are usually noisier than helical gears because fewer teeth are in contact (lower contact ratio). Dynamic loads on gear teeth and bearings may be greater than with helical gears. Size for size, spur gears have less load capacity than helical gears.

Spur gears are often used in epicyclic gearboxes because they avoid the tendency of helical gears to misalign planet gears and interfere with free-floating sun pinions. Most importantly, they provide self-aligning planet gears because each planet can have a single, spherical-roller bearing. For these reasons, many wind turbine gearboxes have spur gears in the LS planetary gearset. However, several turbines larger than 750 kW have helical gears in the LS planetary gearset to control noise level. A few gearboxes for small turbines (≤ 250 kW) have spur gears in the LS and HS gearsets. GEARTECH is not aware of a 500 kW wind turbine gearbox with spur gears in the HS gearset.

It will be challenging to achieve a quiet gearbox with spur gears in the HS gearset. In addition to low contact ratio, spur gears are totally dependent on the accuracy of gear tooth profiles, and excessive wear on profiles causes noisy gears. As shown in Table 3, the probability of wear is very high. Furthermore, the gearbox has an integral wet brake, which will contaminate the lubricant with wear debris. Low viscosity lubricant contaminated with brake debris is likely to promote micropitting, which is especially damaging to spur gears because micropitting tends to preferentially attack pinion dedenda and cause disparity between base pitches of pinion and gear. Dynamic loads caused by spacing errors may lead to noisy gears or gear failure.

GEARTECH DOC:010925-WTC-3 [1] shows the tip diameters of the LS sun, HS sun, and HS planet are smaller than recommended. This results in less contact ratio than necessary and may increase noise level.

WTC drawings [6] default to Flender proprietary specifications for gear tooth profile modifications. Spur gears are very sensitive to profile modifications. Therefore, WTC should not rely on undisclosed features, and should show profile charts on the engineering drawings that fully specify profile modification. GEARTECH DOC:011003-WTC-5 [1] gives recommended profile and helix charts.

WTC drawings [6] for the annulus gears specify through hardened, shaper-cut gear teeth, and relatively low gear tooth accuracy. This processing gives rough, soft gear tooth surfaces that are likely to promote wear and generate noise. Annulus gears should be surface-hardened and teeth should be ground or shaved to obtain smooth surfaces with adequate accuracy. However, the configuration of the LS annulus gear does not allow adequate room for runout of a grinding wheel. Therefore, the LS annulus should be changed to a two-piece construction to allow gear tooth grinding. The design of the HS and LS annulus gears should be changed to specify either carburized or nitrided heat treatment. If carburized, gears should be ground after heat treatment. If nitrided, gears should be ground or shaved before heat treatment.

Gear Tooth Rating

Table 1 shows the LS sun has inadequate Hertzian life. This is primarily caused by the low number of teeth (only 17). Pinions should have at least 20 teeth to achieve a good balance between pitting resistance, bending strength, and scuffing resistance. More teeth would increase the contact ratio and reduce noise level. Table 2 shows bending fatigue life is more than adequate, allowing more teeth by using a smaller module. Scuffing, micropitting, and wear resistance would also increase with more teeth.

Gear Tooth Metallurgy

WTC drawings [6] specify ISO 6336-5 [7] grade ME metallurgical quality for the sun and planet gears. However, ISO 6336-5 is not comprehensive and must be supplemented to adequately control metallurgical quality. Therefore, recommendations given in GEARTECH DOC:011002-WTC-4 [1] for specifications and quality procedures for achieving adequate metallurgical quality should be followed.

WTC drawings specify through hardened annulus gears. The relatively soft surfaces of through hardened gears are vulnerable to trapping contaminants. Hard particles embedded in through-hardened annulus gears cause polishing (fine-scale abrasive wear) on mating planet gears. This degrades gear accuracy and generates wear debris. It is especially damaging to spur gears (see *Spur versus Helical Gears* for further information on metallurgy of annulus gears).

Lubrication

The lubricant specified by WTC is Mobilfluid 424. It is a hydraulic fluid intended for tractor transmissions with wet brakes. The Mobil Product Data Sheet shows it is a mineral oil with a

viscosity of 55 cSt at 40°C. It has a relatively high viscosity index (VI) of 152, which indicates it is formulated with a viscosity-index improver.

Wind turbine gearboxes require a lubricant with at least ISO 320 viscosity. With only ISO 55 viscosity, there is a high risk of micropitting. Although the lubricant has a relatively high VI, it is achieved with a viscosity-index improver, which are known to degrade under the high shear rates attained in gear teeth and bearings. Furthermore, WTC drawings do not specify surface roughness for gear teeth. Therefore, gear tooth surfaces may be rough, and the risk of micropitting increased.

Wear debris from the wet brake may contaminate the lubricant, cause polishing wear on planet gears, promote micropitting, and shorten the fatigue life of gears and bearings.

Recommended Tests

Sound emission testing should be a first priority. If the operating sound level is unacceptable, there is no point in further testing, and redesign is necessary. The gearbox should be run-in under a series of controlled loads to improve surface roughness before applying the maximum load.

After sound emission testing, full-load tests should be conducted to determine micropitting resistance. The lubrication system and lubricant should be identical to production gearboxes, except lubricant temperature should be controlled to simulate maximum temperature likely to be encountered in service. Often micropitting occurs in less than 10^6 cycles. Therefore, only a few days should be sufficient to disclose whether micropitting will occur. Gear tooth surfaces should be inspected frequently during subsequent tests to ensure micropitting does not occur.

If sound level is acceptable, and micropitting does not occur, endurance load tests should be conducted to determine if gears and bearings have adequate fatigue life. Analysis is required to determine the endurance load required to simulate 20 year life. The endurance load must not be too high. Otherwise, gear tooth profile and lead modifications will be inadequate, and tip-to-root interference or edge contact may occur.

Applicable Documents

1. GEARTECH letters to WTC:

| Document No. | Subject |
|-------------------------|---|
| DOC:010921-WTC-1 | Audit-1 of engineering drawings |
| DOC:010924-WTC-2 | Audit-2 of engineering drawings-bearing fits |
| DOC:010925-WTC-3 | Audit-3 of engineering drawings-tip diameters |
| DOC:011002-WTC-4 | Audit-4 of engineering drawings-drawing notes |
| DOC:011003-WTC-5 | Audit-5 of engineering drawings-chamfers and charts |

2. AGMA218 Computer Program, Copyright GEARTECH Software, Inc. 1985-2002.
3. ANSI/AGMA 2001-C95, "AMERICAN NATIONAL STANDARD- Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth," January 1995.
4. SCORING+ Computer Program, Copyright GEARTECH Software, Inc. 1985-2002.
5. SKF General Catalog 4000 US Second Edition, 1997.
6. WTC engineering drawings:

| Title | Drawing No. | Revision |
|-------------------------|--------------------|-----------------|
| Assembly drawing | 2040A | A |
| LS sun | 2032C | C |
| LS planet | 2034B | B |
| LS annulus | 2032A | A |
| HS sun | 2033C | C |
| HS planet | 2035C | C |
| HS annulus | 2135B | B |

7. ISO 6336-5:1996, "Calculation of load capacity of spur and helical gears- Part 5: Strength and quality of materials."

Appendix A
Load Spectrum

EMD-1 Gearbox Torque Spectrum

Derived from GHP-0065-D

Original data obtained from WTC

Gear Ratio: 60.565
Stage 1 Designation: M9-115/49/17
Stage 2 Designation: M6-136/58/20
Synch Rotor Speed: 29.72 rpm

| Torque at Gearbox Input Shaft (kNm) | Cumulative Revolutions at Gearbox Input Shaft in 20 Year Design Life |
|--|---|
| -66.81 | 8.40E+01 |
| -63.24 | 8.52E+01 |
| -59.67 | 0.00E+00 |
| -56.11 | 8.31E+01 |
| -52.54 | 0.00E+00 |
| -48.97 | 8.66E+01 |
| -45.41 | 0.00E+00 |
| -41.84 | 0.00E+00 |
| -38.28 | 4.45E+01 |
| -34.71 | 1.26E+02 |
| -31.14 | 1.31E+02 |
| -27.58 | 0.00E+00 |
| -24.01 | 8.60E+01 |
| -20.44 | 4.65E+03 |
| -16.88 | 2.51E+04 |
| -13.31 | 6.82E+04 |
| -9.74 | 9.78E+04 |
| -6.18 | 1.57E+05 |
| -2.61 | 5.23E+05 |
| 0.95 | 1.02E+06 |
| 4.52 | 1.66E+06 |
| 8.09 | 2.28E+06 |
| 11.65 | 2.78E+06 |
| 15.22 | 3.21E+06 |
| 18.79 | 3.60E+06 |
| 22.35 | 3.84E+06 |
| 25.92 | 4.15E+06 |
| 29.49 | 4.35E+06 |
| 33.05 | 4.27E+06 |
| 36.62 | 4.50E+06 |
| 40.18 | 4.47E+06 |
| 43.75 | 4.58E+06 |
| 47.32 | 4.59E+06 |
| 50.88 | 4.50E+06 |
| 54.45 | 4.89E+06 |
| 58.02 | 4.72E+06 |
| 61.58 | 4.79E+06 |
| 65.15 | 4.24E+06 |

| | |
|--------|----------|
| 68.72 | 4.53E+06 |
| 72.28 | 4.48E+06 |
| 75.85 | 4.34E+06 |
| 79.41 | 4.26E+06 |
| 82.98 | 4.22E+06 |
| 86.55 | 4.27E+06 |
| 90.11 | 4.41E+06 |
| 93.68 | 3.99E+06 |
| 97.25 | 3.95E+06 |
| 100.81 | 3.94E+06 |
| 104.38 | 3.90E+06 |
| 107.94 | 3.81E+06 |
| 111.51 | 3.79E+06 |
| 115.08 | 3.80E+06 |
| 118.64 | 3.59E+06 |
| 122.21 | 3.60E+06 |
| 125.78 | 3.62E+06 |
| 129.34 | 3.59E+06 |
| 132.91 | 3.50E+06 |
| 136.48 | 3.59E+06 |
| 140.04 | 3.82E+06 |
| 143.61 | 3.92E+06 |
| 147.17 | 4.20E+06 |
| 150.74 | 4.41E+06 |
| 154.31 | 4.71E+06 |
| 157.87 | 4.93E+06 |
| 161.44 | 5.30E+06 |
| 165.01 | 5.55E+06 |
| 168.57 | 5.65E+06 |
| 172.14 | 5.65E+06 |
| 175.71 | 5.54E+06 |
| 179.27 | 5.25E+06 |
| 182.84 | 4.81E+06 |
| 186.40 | 4.35E+06 |
| 189.97 | 3.77E+06 |
| 193.54 | 3.10E+06 |
| 197.10 | 2.50E+06 |
| 200.67 | 1.98E+06 |
| 204.24 | 1.50E+06 |
| 207.80 | 1.10E+06 |
| 211.37 | 7.87E+05 |
| 214.94 | 5.67E+05 |
| 218.50 | 4.09E+05 |
| 222.07 | 2.83E+05 |
| 225.63 | 1.93E+05 |
| 229.20 | 1.25E+05 |
| 232.77 | 9.24E+04 |
| 236.33 | 5.82E+04 |
| 239.90 | 3.72E+04 |
| 243.47 | 3.15E+04 |
| 247.03 | 1.82E+04 |

| | |
|--------|----------|
| 250.60 | 1.31E+04 |
| 254.17 | 1.00E+04 |
| 257.73 | 5.95E+03 |
| 261.30 | 6.26E+03 |
| 264.86 | 3.49E+03 |
| 268.43 | 3.20E+03 |
| 272.00 | 2.40E+03 |
| 275.56 | 1.83E+03 |
| 279.13 | 2.31E+03 |
| 282.70 | 1.50E+03 |
| 286.26 | 9.10E+02 |
| 289.83 | 7.37E+02 |
| 293.40 | 5.73E+02 |
| 296.96 | 3.39E+02 |
| 300.53 | 1.85E+02 |
| 304.09 | 9.28E+01 |
| 307.66 | 1.34E+02 |
| 311.23 | 4.64E+01 |
| 314.79 | 4.61E+01 |
| 318.36 | 1.86E+02 |
| 321.93 | 4.73E+01 |
| 325.49 | 0.00E+00 |
| 329.06 | 8.99E+01 |
| 332.62 | 1.39E+02 |
| 336.19 | 0.00E+00 |
| 339.76 | 4.69E+01 |
| 343.32 | 2.74E+02 |
| 346.89 | 1.39E+02 |
| 350.46 | 4.79E+01 |
| 354.02 | 1.37E+02 |
| 357.59 | 0.00E+00 |
| 361.16 | 0.00E+00 |
| 364.72 | 4.66E+01 |
| 368.29 | 0.00E+00 |
| 371.85 | 0.00E+00 |
| 375.42 | 4.74E+01 |
| 378.99 | 4.80E+01 |
| 382.55 | 0.00E+00 |

Reduced load spectrum- The following procedure was used to reduce the number of loads to 50:

- Negative loads were discarded.
- Loads in range $0.95 \leq T \leq 90.11$ kNm combined into one load of magnitude 90.11 kNm and cumulative cycles of 1.03×10^8 revolutions.
- Loads in range $93.68 \leq T \leq 154.31$ kNm reduced from 18 to 9 by combining pairs of loads into one bin using the higher torque and summing the revolutions.
- Twenty four loads in the range $157.87 \leq T \leq 239.90$ kNm used as is.
- Loads in range $243.47 \leq T \leq 354.02$ kNm reduced from 32 to 15 by eliminating those with zero cumulative revolutions and combining pairs of adjacent loads into one bin using the higher torque and summing the revolutions.
- Load 50 taken as 378.99 kNm and summing the revolutions of loads in the range $357.59 \leq T \leq 378.99$ kNm.

Definitions

Baseline torque $T_b = 160,654$ Nm

Total cumulative cycles $\sum n_i = 2.363 \times 10^8$ cycles

Load ratio $\beta_i = T_i/T_b$

Cycle ratio $\alpha_i = n_i/\sum n_i$

Ratio of equivalent dynamic load to baseline load used for bearing rating:

$$P_{\text{equiv}}/P_{\text{rated}} = \{((\beta_i)^{10/3}) * \alpha_i\}^{3/10}$$

For the reduced spectrum, $P_{\text{equiv}}/P_{\text{rated}} = 0.8608514$

$\therefore P_{\text{equiv}} = 0.860851(500) = 430.43$ kW

| EMD-1 Gearbox Torque Spectrum Reduced to 50 loads | | | | |
|---|--------------------------------------|-----------------|-------------------|-----------------------------|
| Rotor Torque (kNm) | Cumulative rotor revs in 20 years | Load Ratio Beta | Cycle Ratio Alpha | beta ^{10/3} alpha |
| 90.1131300 | 1.0296050E+08 | 0.560914 | 0.435701 | 0.063412842 |
| 97.2458300 | 7.9320110E+06 | 0.605312 | 0.033566 | 0.006297472 |
| 104.3785000 | 7.8389620E+06 | 0.649710 | 0.033172 | 0.007879677 |
| 111.5112000 | 7.5932860E+06 | 0.694108 | 0.032133 | 0.009514173 |
| 118.6439000 | 7.3893000E+06 | 0.738506 | 0.031270 | 0.01138416 |
| 125.7766000 | 7.2128120E+06 | 0.782904 | 0.030523 | 0.013499482 |
| 132.9093000 | 7.0867070E+06 | 0.827302 | 0.029989 | 0.015940748 |
| 140.0420000 | 7.4091970E+06 | 0.871699 | 0.031354 | 0.019838636 |
| 147.1747000 | 8.1186860E+06 | 0.916097 | 0.034356 | 0.025653262 |
| 154.3074000 | 9.1223770E+06 | 0.960495 | 0.038603 | 0.033750239 |
| 157.8738000 | 4.9321260E+06 | 0.982694 | 0.020871 | 0.019691586 |
| 161.4401000 | 5.2955170E+06 | 1.00489 | 0.022409 | 0.022776802 |
| 165.0065000 | 5.5486970E+06 | 1.02709 | 0.023481 | 0.025668915 |
| 168.5728000 | 5.6498540E+06 | 1.04929 | 0.023909 | 0.028067812 |
| 172.1392000 | 5.6519850E+06 | 1.07149 | 0.023918 | 0.030107863 |
| 175.7055000 | 5.5380040E+06 | 1.09369 | 0.023435 | 0.031587659 |
| 179.2719000 | 5.2471300E+06 | 1.11589 | 0.022204 | 0.032001885 |
| 182.8382000 | 4.8140050E+06 | 1.13809 | 0.020372 | 0.031352775 |
| 186.4046000 | 4.3534570E+06 | 1.16029 | 0.018423 | 0.030239133 |
| 189.9709000 | 3.7717520E+06 | 1.18248 | 0.015961 | 0.027906994 |
| 193.5373000 | 3.1039940E+06 | 1.20468 | 0.013135 | 0.024435213 |
| 197.1036000 | 2.5006320E+06 | 1.22688 | 0.010582 | 0.020920785 |
| 200.6700000 | 1.9848610E+06 | 1.24908 | 0.008399 | 0.017628604 |
| 204.2363000 | 1.4960760E+06 | 1.27128 | 0.006331 | 0.014091042 |
| 207.8027000 | 1.1025030E+06 | 1.29348 | 0.004665 | 0.011000947 |
| 211.3690000 | 7.8719330E+05 | 1.31568 | 0.003331 | 0.008313145 |
| 214.9354000 | 5.6660080E+05 | 1.33788 | 0.002398 | 0.006326789 |
| 218.5017000 | 4.0878550E+05 | 1.36008 | 0.001730 | 0.00482197 |
| 222.0680000 | 2.8282370E+05 | 1.38227 | 0.001197 | 0.00352113 |
| 225.6344000 | 1.9340580E+05 | 1.40447 | 0.000818 | 0.002539219 |
| 229.2007000 | 1.2504450E+05 | 1.42667 | 0.000529 | 0.001729806 |
| 232.7671000 | 9.2362060E+04 | 1.44887 | 0.000391 | 0.001345174 |
| 236.3334000 | 5.8193250E+04 | 1.47107 | 0.000246 | 0.000891598 |
| 239.8998000 | 3.7165850E+04 | 1.49327 | 0.000157 | 0.000598582 |
| 247.0325000 | 4.9662130E+04 | 1.53767 | 0.000210 | 0.000881899 |
| 254.1652000 | 2.3104540E+04 | 1.58207 | 0.000098 | 0.000451125 |
| 261.2979000 | 1.2205318E+04 | 1.62646 | 0.000052 | 0.000261346 |
| 268.4306000 | 6.6877190E+03 | 1.67086 | 0.000028 | 0.00015665 |
| 275.5633000 | 4.2333080E+03 | 1.71526 | 0.000018 | 0.000108217 |
| 282.6960000 | 3.8146140E+03 | 1.75966 | 0.000016 | 0.000106185 |
| 289.8287000 | 1.6473173E+03 | 1.80406 | 7.0E-06 | 4.98266E-05 |
| 296.9614000 | 9.1177680E+02 | 1.84845 | 3.9E-06 | 2.99067E-05 |
| 304.0941000 | 2.7769665E+02 | 1.89285 | 1.2E-06 | 9.85849E-06 |
| 311.2268000 | 1.7997028E+02 | 1.93725 | 7.6E-07 | 6.90246E-06 |
| 318.3595000 | 2.3180508E+02 | 1.98165 | 9.8E-07 | 9.58801E-06 |
| 329.0585000 | 1.3724475E+02 | 2.04824 | 5.8E-07 | 6.338E-06 |
| 339.7576000 | 1.8569256E+02 | 2.11484 | 7.9E-07 | 9.54051E-06 |
| 346.8903000 | 4.1278680E+02 | 2.15924 | 1.7E-06 | 2.27289E-05 |
| 354.0230000 | 1.8499508E+02 | 2.20364 | 7.8E-07 | 1.09013E-05 |
| 378.9874000 | 1.4200000E+02 | 2.35903 | 6.0E-07 | 1.05015E-05 |
| | 2.3631002E+08 | | 1.0000E+00 | 0.606867637 sum |
| | | | | 0.860851407 sum^3/10 |

Appendix B
Gear Rating

*****INPUT DATA SUMMARY-1*****

GEAR GEOMETRY DATA

| | PINION | GEAR |
|---------------------------------|------------------|---------|
| TOOTH NUMBER | NP,NG = 17. | 49. |
| NET FACE WIDTH (IN.) | F1,F2 = 5.7087 | 5.7087 |
| OUTSIDE DIAMETER (IN.) | do,Do = 6.9590 | 18.2960 |
| INTERNAL GEAR I.D. (IN.) | Di = | 0.0000 |
| NORMAL DIAMETRAL PITCH | Pnd = 2.8222 | |
| NORMAL PRESSURE ANGLE (DEG.) | PHI(c) = 20.0000 | |
| STANDARD HELIX ANGLE (DEG.) | PSI(s) = 0.0000 | |
| OPERATING CENTER DISTANCE (IN.) | C = 11.9685 | |

GEAR GEOMETRY DATA FOR Pnd = 1.0

| | | |
|---|----------------|--------|
| ADDENDUM MODIFICATION COEFFICIENT | X1,X2 = 0.4600 | 0.3819 |
| THINNING FOR BACKLASH DELTA(sn1),DELTA(sn2) | = 0.0298 | 0.0056 |
| STOCK ALLOW. PER SIDE FOR FINISHING Us1,Us2 | = 0.0261 | 0.0261 |

TOOL GEOMETRY DATA FOR Pnd = 1.0

| | | |
|---------------------------------------|--------------------|--------|
| TOOL NORMAL TOOTH THICKNESS | tce1,tce2 = 1.5185 | 1.5185 |
| TOOL ADDENDUM | hao1,hao2 = 1.4000 | 1.4000 |
| TOOL TIP RADIUS | rTe1,rTe2 = 0.4000 | 0.4000 |
| TOOL PROTUBERANCE DELTA(o1),DELTA(o2) | = 0.0361 | 0.0361 |

MATERIALS/HEAT TREATMENT DATA

| | | |
|-----------------------------|----------------------|---------------|
| MODULUS OF ELASTICITY (PSI) | EP,EG = 30,000,000. | 30,000,000. |
| POISSON'S RATIO | MU(P),MU(G) = 0.3000 | 0.3000 |
| BRINELL HARDNESS | HBP,HBG = 654 | 654 |
| MATERIAL (CODE) | = STEEL(1) | STEEL(1) |
| MATERIAL GRADE | = 2 | 2 |
| HEAT-TREATMENT (CODE) | = CARBURIZED(4) | CARBURIZED(4) |

LOAD DATA

| | | |
|-----------------------------------|-----------------|---|
| TRANSMITTED POWER (HP) | P = 194.7195 | |
| PINION SPEED (rpm) | n(P) = 201.0471 | |
| GEAR BLANK TEMPERATURE (DEG. F) | Tb = 185. | |
| RELIABILITY | R = 0.9900 | |
| NUMBER OF CONTACTS PER REVOLUTION | = 3 | 1 |
| REVERSED BENDING? | = N | Y |
| SPUR GEAR LOADING TYPE | = HPSTC (1) | |

DERATING FACTORS

| | | |
|--|-------------|--|
| APPLICATION FACTOR FOR PITTING RESIST. | Ca = 1.0000 | |
| SIZE FACTOR FOR PITTING RESISTANCE | Cs = 1.0000 | |
| SURFACE CONDITION FACTOR | Cf = 1.0000 | |
| LOAD DIST. FACTOR FOR PITTING RESIST. | Cm = 1.0700 | |
| DYNAMIC FACTOR FOR PITTING RESISTANCE | Cv = 0.9560 | |

RUNTIME OPTIONS

| | |
|-----------------------------|----------------|
| TYPE OF ANALYSIS CHOSEN | = MINER'S RULE |
| CURVE CHOSEN, FIGS. 20 & 21 | = LOWER |

*****GEOMETRY SUMMARY-1*****

| | | PINION | GEAR |
|----------------------|----------|--------|---------|
| GENERATING PITCH DIA | ds, Ds = | 6.0236 | 17.3622 |
| OPERATING PITCH DIA | d, D = | 6.1656 | 17.7714 |
| BASE DIA | db, Db = | 5.6604 | 16.3151 |
| MEAN DIA of PINION | dm = | 6.3000 | |

PRESSURE ANGLES

| | | |
|----------------------|----------|---------|
| STANDARD TRANSVERSE | PHI(s) = | 20.0000 |
| OPERATING TRANSVERSE | PHI(t) = | 23.3566 |
| STANDARD NORMAL | PHI(c) = | 20.0000 |
| OPERATING NORMAL | PHI(n) = | 23.3566 |

HELIX ANGLES

| | | |
|-----------|----------|--------|
| STANDARD | PSI(s) = | 0.0000 |
| OPERATING | PSI = | 0.0000 |
| BASE | PSI(b) = | 0.0000 |

PITCHES

| | | |
|----------------------|------|--------|
| TRANSVERSE DIAMETRAL | Pd = | 2.8222 |
| TRANSVERSE BASE | pb = | 1.0460 |
| NORMAL BASE | pN = | 1.0460 |
| AXIAL | px = | 0.0000 |

DISTANCES ALONG LINE OF ACTION (FIG. 1)

| | | |
|---------------------------------------|------|--------|
| ACTIVE LENGTH OF LINE OF ACTION | Z = | 1.4192 |
| PINION ADDENDUM PORTION OF Z | Za = | 0.8019 |
| PINION DEDENDUM PORTION OF Z | Zb = | 0.6173 |
| DIST. FROM PITCH POINT TO STRESS CALC | Zc = | 0.2441 |

RATIOS

| | | |
|------------------------------|------|--------|
| GEAR | mG = | 2.8824 |
| TRANSVERSE (PROFILE) CONTACT | mp = | 1.3568 |
| AXIAL (FACE) CONTACT | mF = | 0.0000 |
| LOAD SHARING (mN = F/Lmin) | mN = | 1.0000 |

TRANSVERSE RADII OF CURVATURE

| | | |
|------------------------------------|------|--------|
| AT OPERATING PITCH POINT OF PINION | RP = | 1.2222 |
| AT OPERATING PITCH POINT OF GEAR | RG = | 3.5228 |
| AT POINT OF STRESS CALC OF PINION | R1 = | 0.9781 |
| AT POINT OF STRESS CALC OF GEAR | R2 = | 3.7669 |

NOTE: All dims in inches, all angles in degrees.

=====
GEOMETRY SUMMARY-2
=====

PITTING RESISTANCE GEOMETRY FACTOR DATA

| | | |
|------------------------------------|----------|--------|
| GEAR RATIO FACTOR | CG = | 0.7424 |
| CURVATURE FACTOR | Cc = | 0.1351 |
| CONTACT HEIGHT FACTOR | Cx = | 0.8557 |
| CONTACT HEIGHT FACTOR (LCR) | Cxh = | 1.0799 |
| HELICAL OVERLAP FACTOR | C(PSI) = | 1.0000 |
| MINIMUM LENGTH OF CONTACT | Lmin = | 5.7087 |
| PITTING RESISTANCE GEOMETRY FACTOR | I = | 0.1156 |

BENDING STRENGTH GEOMETRY FACTOR DATA

| | | PINION | GEAR |
|-------------------------------------|----------|--------|--------|
| LOAD ANGLE | PHI(L) = | 0.4581 | 0.4092 |
| HEIGHT OF LEWIS PARABOLA | h = | 1.2329 | 1.3893 |
| TOOTH THICKNESS AT CRITICAL SECTION | t = | 2.0755 | 2.2483 |
| HELICAL FACTOR | Ch = | 1.0000 | 1.0000 |
| HELIX ANGLE FACTOR | K(PSI) = | 1.0000 | 1.0000 |
| STRESS CORRECTION FACTOR | Kf = | 1.7768 | 1.7798 |
| TOOTH FORM FACTOR | Y = | 0.6918 | 0.6873 |
| BENDING STRENGTH GEOMETRY FACTOR | J = | 0.3893 | 0.3861 |

=====
LOAD SUMMARY
=====

| | | |
|---|--------|-----------|
| PITCH LINE VELOCITY (FPM) | vt = | 325. |
| TRANSMITTED TANGENTIAL LOAD (LB.) | Wt = | 19,801. |
| TORQUE TRANSMITTED BY PINION (LB.IN.) | T(1) = | 6.10D+004 |
| TORQUE TRANSMITTED BY GEAR (LB.IN.) | T(2) = | 1.76D+005 |
| CONTACT LOAD FACTOR FOR PITTING RESIST. | K = | 758. |
| UNIT LOAD FACTOR FOR BENDING STRENGTH | U(L) = | 9,789. |

=====
DERATING FACTOR SUMMARY
=====

| | | |
|------------------------------|----------|--------|
| APPLICATION | Ca, Ka = | 1.0000 |
| SIZE | Cs, Ks = | 1.0000 |
| LOAD DISTRIBUTION | Cm, Km = | 1.0700 |
| DYNAMIC | Cv, Kv = | 0.9560 |
| SURFACE CONDITION | Cf = | 1.0000 |
| COMBINED DURABILITY DERATING | C(D) = | 1.1192 |
| COMBINED STRENGTH DERATING | K(D) = | 1.1192 |

NOTE: Transverse Load Distribution Factor Cmt = 1.0

=====
STRENGTH SUMMARY
=====

| | | |
|--|-------------|--------------|
| HARDNESS RATIO FACTOR | C(H) = | 1.0000 |
| TEMPERATURE FACTOR | C(T),K(T) = | 1.0000 |
| RELIABILITY FACTOR | C(R),K(R) = | 1.0000 |
| ALLOW. CONTACT STRESS NO.,PINION (PSI) | Sac1 = | 225,000. *a* |
| ALLOW. CONTACT STRESS NO.,GEAR (PSI) | Sac2 = | 225,000. *a* |
| ALLOW. BENDING STRESS NO.,PINION (PSI) | Sat1 = | 70,000. *a* |
| ALLOW. BENDING STRESS NO.,GEAR (PSI) | Sat2 = | 49,000. *a* |

a NOTE: Based on allowable stresses at 10^7 cycles to failure.
with effects of C(H), C(T), & C(R).

=====
STRESS SUMMARY
=====

| | | |
|---------------------------------|-------|----------|
| ELASTIC COEFFICIENT | Cp = | 2,291. |
| CONTACT STRESS NO. (PSI) | Sc = | 169,040. |
| PINION BENDING STRESS NO. (PSI) | St1 = | 28,142. |
| GEAR BENDING STRESS NO. (PSI) | St2 = | 28,374. |

=====
HERTZIAN LIFE
PINION
=====

| CASE IDENT: | WTC LS/SP | | | |
|--------------|----------------------|-----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 126601. | 2.88D+011 | 2.40D-003 |
| .605312 | .033566 | 131516. | 1.46D+011 | 3.64D-004 |
| .64971 | .033172 | 136254. | 7.76D+010 | 6.78D-004 |
| .694108 | .032133 | 140833. | 4.30D+010 | 1.18D-003 |
| .738506 | .03127 | 145267. | 2.47D+010 | 2.00D-003 |
| .782904 | .030523 | 149570. | 1.47D+010 | 3.30D-003 |
| .827302 | .029989 | 153752. | 8.97D+009 | 5.30D-003 |
| .871699 | .031354 | 157824. | 5.62D+009 | 8.83D-003 |
| .916097 | .034356 | 161793. | 3.61D+009 | 1.51D-002 |
| .960495 | .038603 | 165667. | 2.37D+009 | 2.59D-002 |
| .982694 | .020871 | 167571. | 1.93D+009 | 1.71D-002 |
| 1.00489 | .022409 | 169453. | 1.58D+009 | 2.25D-002 |
| 1.02709 | .023481 | 171314. | 1.30D+009 | 2.86D-002 |
| 1.04929 | .023909 | 173156. | 1.07D+009 | 3.53D-002 |
| 1.07149 | .023918 | 174978. | 8.91D+008 | 4.25D-002 |
| 1.09369 | .023435 | 176782. | 7.42D+008 | 5.01D-002 |
| 1.11589 | .022204 | 178567. | 6.20D+008 | 5.67D-002 |
| 1.13809 | .020372 | 180334. | 5.20D+008 | 6.21D-002 |
| 1.16029 | .018423 | 182085. | 4.38D+008 | 6.67D-002 |
| 1.18248 | .015961 | 183817. | 3.70D+008 | 6.84D-002 |
| 1.20468 | .013135 | 185535. | 3.13D+008 | 6.65D-002 |
| 1.22688 | .010582 | 187237. | 2.66D+008 | 6.31D-002 |
| 1.24908 | .008399 | 188923. | 2.27D+008 | 5.87D-002 |
| 1.27128 | .006331 | 190594. | 1.94D+008 | 5.18D-002 |
| 1.29348 | .004665 | 192251. | 1.66D+008 | 4.46D-002 |
| 1.31568 | .003331 | 193894. | 1.42D+008 | 3.70D-002 |
| 1.33788 | .002398 | 195523. | 1.23D+008 | 3.10D-002 |
| 1.36008 | .00173 | 197139. | 1.06D+008 | 2.59D-002 |
| 1.38227 | .001197 | 198740. | 9.17D+007 | 2.07D-002 |
| 1.40447 | .000818 | 200330. | 7.95D+007 | 1.63D-002 |
| 1.42667 | .000529 | 201907. | 6.91D+007 | 1.21D-002 |
| 1.44887 | .000391 | 203472. | 6.02D+007 | 1.03D-002 |
| 1.47107 | .000246 | 205025. | 5.26D+007 | 7.41D-003 |
| 1.49327 | .000157 | 206566. | 4.60D+007 | 5.41D-003 |
| 1.53767 | .00021 | 209614. | 3.54D+007 | 9.40D-003 |
| 1.58207 | .000098 | 212619. | 2.75D+007 | 5.65D-003 |
| 1.62646 | .000052 | 215581. | 2.15D+007 | 3.84D-003 |
| 1.67086 | .000028 | 218504. | 1.69D+007 | 2.63D-003 |
| 1.71526 | .000018 | 221388. | 1.33D+007 | 2.14D-003 |
| 1.75966 | .000016 | 224235. | 1.06D+007 | 2.39D-003 |
| 1.80406 | .000007 | 227047. | 8.50D+006 | 1.30D-003 |
| 1.84845 | .000004 | 229823. | 6.85D+006 | 9.26D-004 |
| 1.89285 | .000001 | 232567. | 5.54D+006 | 2.86D-004 |

GEARTECH
CASE IDENT: WTC LS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 6

=====
HERTZIAN LIFE
PINION (Continued)
=====

| CASE IDENT: | WTC LS/SP | | | |
|--------------|----------------------|-----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| 1.93725 | 7.6E-07 | 235279. | 4.50D+006 | 2.67D-004 |
| 1.98165 | 9.8E-07 | 237960. | 3.68D+006 | 4.22D-004 |
| 2.04824 | 5.8E-07 | 241925. | 2.74D+006 | 3.36D-004 |
| 2.11484 | 7.9E-07 | 245826. | 2.06D+006 | 6.08D-004 |
| 2.15924 | .000002 | 248393. | 1.71D+006 | 1.85D-003 |
| 2.20364 | 7.8E-07 | 250934. | 1.43D+006 | 8.67D-004 |
| 2.35903 | .0000006 | 259631. | 7.76D+005 | 1.23D-003 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE HERTZIAN STRESS Sc = 1.69D+005
RESULTANT HERTZIAN LIFE Nc = 1.58D+009 CYCLES
RESULTANT HERTZIAN LIFE Nc = 4.38D+004 HOURS

=====
****BENDING LIFE****
PINION
=====

| CASE IDENT: | WTC LS/SP | | | |
|--------------|----------------------|----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 15785. | 1.06D+027 | 2.42D-014 |
| .605312 | .033566 | 17035. | 1.01D+026 | 1.97D-014 |
| .64971 | .033172 | 18284. | 1.12D+025 | 1.74D-013 |
| .694108 | .032133 | 19533. | 1.45D+024 | 1.31D-012 |
| .738506 | .03127 | 20783. | 2.13D+023 | 8.67D-012 |
| .782904 | .030523 | 22032. | 3.49D+022 | 5.16D-011 |
| .827302 | .029989 | 23282. | 6.33D+021 | 2.79D-010 |
| .871699 | .031354 | 24531. | 1.26D+021 | 1.47D-009 |
| .916097 | .034356 | 25781. | 2.70D+020 | 7.52D-009 |
| .960495 | .038603 | 27030. | 6.23D+019 | 3.66D-008 |
| .982694 | .020871 | 27655. | 3.07D+019 | 4.01D-008 |
| 1.00489 | .022409 | 28279. | 1.54D+019 | 8.60D-008 |
| 1.02709 | .023481 | 28904. | 7.82D+018 | 1.77D-007 |
| 1.04929 | .023909 | 29529. | 4.03D+018 | 3.50D-007 |
| 1.07149 | .023918 | 30154. | 2.11D+018 | 6.69D-007 |
| 1.09369 | .023435 | 30778. | 1.12D+018 | 1.24D-006 |
| 1.11589 | .022204 | 31403. | 6.00D+017 | 2.18D-006 |
| 1.13809 | .020372 | 32028. | 3.26D+017 | 3.69D-006 |
| 1.16029 | .018423 | 32653. | 1.79D+017 | 6.06D-006 |
| 1.18248 | .015961 | 33277. | 9.97D+016 | 9.44D-006 |
| 1.20468 | .013135 | 33902. | 5.61D+016 | 1.38D-005 |
| 1.22688 | .010582 | 34526. | 3.19D+016 | 1.96D-005 |
| 1.24908 | .008399 | 35151. | 1.83D+016 | 2.71D-005 |
| 1.27128 | .006331 | 35776. | 1.06D+016 | 3.53D-005 |
| 1.29348 | .004665 | 36401. | 6.20D+015 | 4.44D-005 |
| 1.31568 | .003331 | 37025. | 3.66D+015 | 5.37D-005 |
| 1.33788 | .002398 | 37650. | 2.18D+015 | 6.49D-005 |
| 1.36008 | .00173 | 38275. | 1.31D+015 | 7.79D-005 |
| 1.38227 | .001197 | 38899. | 7.94D+014 | 8.90D-005 |
| 1.40447 | .000818 | 39524. | 4.85D+014 | 9.96D-005 |
| 1.42667 | .000529 | 40149. | 2.98D+014 | 1.05D-004 |
| 1.44887 | .000391 | 40774. | 1.85D+014 | 1.25D-004 |
| 1.47107 | .000246 | 41398. | 1.16D+014 | 1.26D-004 |
| 1.49327 | .000157 | 42023. | 7.27D+013 | 1.28D-004 |
| 1.53767 | .00021 | 43273. | 2.93D+013 | 4.23D-004 |
| 1.58207 | .000098 | 44522. | 1.22D+013 | 4.76D-004 |
| 1.62646 | .000052 | 45771. | 5.16D+012 | 5.95D-004 |
| 1.67086 | .000028 | 47021. | 2.24D+012 | 7.38D-004 |
| 1.71526 | .000018 | 48270. | 9.95D+011 | 1.07D-003 |
| 1.75966 | .000016 | 49520. | 4.51D+011 | 2.09D-003 |
| 1.80406 | .000007 | 50769. | 2.08D+011 | 1.98D-003 |
| 1.84845 | .000004 | 52019. | 9.82D+010 | 2.40D-003 |
| 1.89285 | .000001 | 53268. | 4.71D+010 | 1.25D-003 |

GEARTECH
CASE IDENT: WTC LS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 8

=====
****BENDING LIFE****
PINION (Continued)
=====

| CASE IDENT: | WTC LS/SP | | | |
|--------------|----------------------|----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| 1.93725 | 7.6E-07 | 54518. | 2.30D+010 | 1.95D-003 |
| 1.98165 | 9.8E-07 | 55767. | 1.14D+010 | 5.08D-003 |
| 2.04824 | 5.8E-07 | 57641. | 4.10D+009 | 8.36D-003 |
| 2.11484 | 7.9E-07 | 59515. | 1.52D+009 | 3.07D-002 |
| 2.15924 | .000002 | 60765. | 7.99D+008 | 1.48D-001 |
| 2.20364 | 7.8E-07 | 62014. | 4.26D+008 | 1.08D-001 |
| 2.35903 | .0000006 | 66387. | 5.16D+007 | 6.86D-001 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE BENDING STRESS St = 2.81D+004
RESULTANT BENDING LIFE Nt = 5.90D+013 CYCLES
RESULTANT BENDING LIFE Nt = 1.63D+009 HOURS

=====
HERTZIAN LIFE
GEAR
=====

| CASE IDENT: | WTC LS/SP | | | |
|--------------|----------------------|-----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 126601. | 2.88D+011 | 2.40D-003 |
| .605312 | .033566 | 131516. | 1.46D+011 | 3.64D-004 |
| .64971 | .033172 | 136254. | 7.76D+010 | 6.78D-004 |
| .694108 | .032133 | 140833. | 4.30D+010 | 1.18D-003 |
| .738506 | .03127 | 145267. | 2.47D+010 | 2.00D-003 |
| .782904 | .030523 | 149570. | 1.47D+010 | 3.30D-003 |
| .827302 | .029989 | 153752. | 8.97D+009 | 5.30D-003 |
| .871699 | .031354 | 157824. | 5.62D+009 | 8.83D-003 |
| .916097 | .034356 | 161793. | 3.61D+009 | 1.51D-002 |
| .960495 | .038603 | 165667. | 2.37D+009 | 2.59D-002 |
| .982694 | .020871 | 167571. | 1.93D+009 | 1.71D-002 |
| 1.00489 | .022409 | 169453. | 1.58D+009 | 2.25D-002 |
| 1.02709 | .023481 | 171314. | 1.30D+009 | 2.86D-002 |
| 1.04929 | .023909 | 173156. | 1.07D+009 | 3.53D-002 |
| 1.07149 | .023918 | 174978. | 8.91D+008 | 4.25D-002 |
| 1.09369 | .023435 | 176782. | 7.42D+008 | 5.01D-002 |
| 1.11589 | .022204 | 178567. | 6.20D+008 | 5.67D-002 |
| 1.13809 | .020372 | 180334. | 5.20D+008 | 6.21D-002 |
| 1.16029 | .018423 | 182085. | 4.38D+008 | 6.67D-002 |
| 1.18248 | .015961 | 183817. | 3.70D+008 | 6.84D-002 |
| 1.20468 | .013135 | 185535. | 3.13D+008 | 6.65D-002 |
| 1.22688 | .010582 | 187237. | 2.66D+008 | 6.31D-002 |
| 1.24908 | .008399 | 188923. | 2.27D+008 | 5.87D-002 |
| 1.27128 | .006331 | 190594. | 1.94D+008 | 5.18D-002 |
| 1.29348 | .004665 | 192251. | 1.66D+008 | 4.46D-002 |
| 1.31568 | .003331 | 193894. | 1.42D+008 | 3.70D-002 |
| 1.33788 | .002398 | 195523. | 1.23D+008 | 3.10D-002 |
| 1.36008 | .00173 | 197139. | 1.06D+008 | 2.59D-002 |
| 1.38227 | .001197 | 198740. | 9.17D+007 | 2.07D-002 |
| 1.40447 | .000818 | 200330. | 7.95D+007 | 1.63D-002 |
| 1.42667 | .000529 | 201907. | 6.91D+007 | 1.21D-002 |
| 1.44887 | .000391 | 203472. | 6.02D+007 | 1.03D-002 |
| 1.47107 | .000246 | 205025. | 5.26D+007 | 7.41D-003 |
| 1.49327 | .000157 | 206566. | 4.60D+007 | 5.41D-003 |
| 1.53767 | .00021 | 209614. | 3.54D+007 | 9.40D-003 |
| 1.58207 | .000098 | 212619. | 2.75D+007 | 5.65D-003 |
| 1.62646 | .000052 | 215581. | 2.15D+007 | 3.84D-003 |
| 1.67086 | .000028 | 218504. | 1.69D+007 | 2.63D-003 |
| 1.71526 | .000018 | 221388. | 1.33D+007 | 2.14D-003 |
| 1.75966 | .000016 | 224235. | 1.06D+007 | 2.39D-003 |
| 1.80406 | .000007 | 227047. | 8.50D+006 | 1.30D-003 |
| 1.84845 | .000004 | 229823. | 6.85D+006 | 9.26D-004 |
| 1.89285 | .000001 | 232567. | 5.54D+006 | 2.86D-004 |

GEARTECH
CASE IDENT: WTC LS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 10

=====
HERTZIAN LIFE
GEAR (Continued)
=====

| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
|------------|-------------|-----------------|-------------------|--------------|
| 1.93725 | 7.6E-07 | 235279. | 4.50D+006 | 2.67D-004 |
| 1.98165 | 9.8E-07 | 237960. | 3.68D+006 | 4.22D-004 |
| 2.04824 | 5.8E-07 | 241925. | 2.74D+006 | 3.36D-004 |
| 2.11484 | 7.9E-07 | 245826. | 2.06D+006 | 6.08D-004 |
| 2.15924 | .000002 | 248393. | 1.71D+006 | 1.85D-003 |
| 2.20364 | 7.8E-07 | 250934. | 1.43D+006 | 8.67D-004 |
| 2.35903 | .0000006 | 259631. | 7.76D+005 | 1.23D-003 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE HERTZIAN STRESS Sc = 1.69D+005
RESULTANT HERTZIAN LIFE Nc = 1.58D+009 CYCLES
RESULTANT HERTZIAN LIFE Nc = 3.79D+005 HOURS

=====
BENDING LIFE
GEAR
=====

| CASE IDENT: | WTC LS/SP | | | |
|--------------|----------------------|----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 15915. | 1.32D+022 | 1.45D-012 |
| .605312 | .033566 | 17175. | 1.25D+021 | 1.18D-012 |
| .64971 | .033172 | 18435. | 1.40D+020 | 1.04D-011 |
| .694108 | .032133 | 19694. | 1.80D+019 | 7.81D-011 |
| .738506 | .03127 | 20954. | 2.64D+018 | 5.18D-010 |
| .782904 | .030523 | 22214. | 4.34D+017 | 3.08D-009 |
| .827302 | .029989 | 23473. | 7.86D+016 | 1.67D-008 |
| .871699 | .031354 | 24733. | 1.56D+016 | 8.81D-008 |
| .916097 | .034356 | 25993. | 3.35D+015 | 4.50D-007 |
| .960495 | .038603 | 27253. | 7.74D+014 | 2.19D-006 |
| .982694 | .020871 | 27882. | 3.81D+014 | 2.40D-006 |
| 1.00489 | .022409 | 28512. | 1.91D+014 | 5.14D-006 |
| 1.02709 | .023481 | 29142. | 9.71D+013 | 1.06D-005 |
| 1.04929 | .023909 | 29772. | 5.01D+013 | 2.09D-005 |
| 1.07149 | .023918 | 30402. | 2.62D+013 | 4.00D-005 |
| 1.09369 | .023435 | 31032. | 1.39D+013 | 7.40D-005 |
| 1.11589 | .022204 | 31662. | 7.45D+012 | 1.31D-004 |
| 1.13809 | .020372 | 32292. | 4.05D+012 | 2.20D-004 |
| 1.16029 | .018423 | 32921. | 2.23D+012 | 3.63D-004 |
| 1.18248 | .015961 | 33551. | 1.24D+012 | 5.65D-004 |
| 1.20468 | .013135 | 34181. | 6.96D+011 | 8.27D-004 |
| 1.22688 | .010582 | 34811. | 3.96D+011 | 1.17D-003 |
| 1.24908 | .008399 | 35441. | 2.27D+011 | 1.62D-003 |
| 1.27128 | .006331 | 36071. | 1.32D+011 | 2.11D-003 |
| 1.29348 | .004665 | 36701. | 7.70D+010 | 2.65D-003 |
| 1.31568 | .003331 | 37330. | 4.55D+010 | 3.21D-003 |
| 1.33788 | .002398 | 37960. | 2.71D+010 | 3.88D-003 |
| 1.36008 | .00173 | 38590. | 1.63D+010 | 4.66D-003 |
| 1.38227 | .001197 | 39220. | 9.86D+009 | 5.32D-003 |
| 1.40447 | .000818 | 39850. | 6.02D+009 | 5.95D-003 |
| 1.42667 | .000529 | 40480. | 3.70D+009 | 6.26D-003 |
| 1.44887 | .000391 | 41110. | 2.30D+009 | 7.46D-003 |
| 1.47107 | .000246 | 41739. | 1.43D+009 | 7.51D-003 |
| 1.49327 | .000157 | 42369. | 9.02D+008 | 7.63D-003 |
| 1.53767 | .00021 | 43629. | 3.64D+008 | 2.53D-002 |
| 1.58207 | .000098 | 44889. | 1.51D+008 | 2.85D-002 |
| 1.62646 | .000052 | 46148. | 6.40D+007 | 3.56D-002 |
| 1.67086 | .000028 | 47408. | 2.78D+007 | 4.41D-002 |
| 1.71526 | .000018 | 48668. | 1.24D+007 | 6.38D-002 |
| 1.75966 | .000016 | 49928. | 5.60D+006 | 1.25D-001 |
| 1.80406 | .000007 | 51188. | 2.88D+006 | 1.06D-001 |
| 1.84845 | .000004 | 52447. | 2.35D+006 | 7.45D-002 |
| 1.89285 | .000001 | 53707. | 1.93D+006 | 2.27D-002 |

GEARTECH
CASE IDENT: WTC LS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 12

=====
****BENDING LIFE****
GEAR (Continued)
=====

| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
|------------|-------------|----------------|-------------------|--------------|
| 1.93725 | 7.6E-07 | 54967. | 1.59D+006 | 2.10D-002 |
| 1.98165 | 9.8E-07 | 56226. | 1.31D+006 | 3.27D-002 |
| 2.04824 | 5.8E-07 | 58116. | 9.94D+005 | 2.56D-002 |
| 2.11484 | 7.9E-07 | 60005. | 7.60D+005 | 4.56D-002 |
| 2.15924 | .000002 | 61265. | 6.38D+005 | 1.37D-001 |
| 2.20364 | 7.8E-07 | 62525. | 5.38D+005 | 6.35D-002 |
| 2.35903 | .0000006 | 66934. | 3.04D+005 | 8.65D-002 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE BENDING STRESS St = 2.84D+004
RESULTANT BENDING LIFE Nt = 4.38D+010 CYCLES
RESULTANT BENDING LIFE Nt = 1.05D+007 HOURS

GEARTECH
CASE IDENT: WTC HS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 1

=====
INPUT DATA SUMMARY-1
=====

GEAR GEOMETRY DATA

| | PINION | GEAR |
|---------------------------------|------------------|---------|
| TOOTH NUMBER | NP,NG = 20. | 58. |
| NET FACE WIDTH (IN.) | F1,F2 = 3.1496 | 3.1496 |
| OUTSIDE DIAMETER (IN.) | do,Do = 5.3530 | 14.3080 |
| INTERNAL GEAR I.D. (IN.) | Di = | 0.0000 |
| NORMAL DIAMETRAL PITCH | Pnd = 4.2333 | |
| NORMAL PRESSURE ANGLE (DEG.) | PHI(c) = 20.0000 | |
| STANDARD HELIX ANGLE (DEG.) | PSI(s) = 0.0000 | |
| OPERATING CENTER DISTANCE (IN.) | C = 9.4094 | |

GEAR GEOMETRY DATA FOR Pnd = 1.0

| | | |
|---|----------------|--------|
| ADDENDUM MODIFICATION COEFFICIENT | X1,X2 = 0.4700 | 0.4260 |
| THINNING FOR BACKLASH DELTA(sn1),DELTA(sn2) | = 0.0333 | 0.0083 |
| STOCK ALLOW. PER SIDE FOR FINISHING Us1,Us2 | = 0.0343 | 0.0343 |

TOOL GEOMETRY DATA FOR Pnd = 1.0

| | | |
|---------------------------------------|--------------------|--------|
| TOOL NORMAL TOOTH THICKNESS | tce1,tce2 = 1.5023 | 1.5023 |
| TOOL ADDENDUM | ha01,ha02 = 1.4000 | 1.4000 |
| TOOL TIP RADIUS | rTe1,rTe2 = 0.4000 | 0.4000 |
| TOOL PROTUBERANCE DELTA(o1),DELTA(o2) | = 0.0443 | 0.0443 |

MATERIALS/HEAT TREATMENT DATA

| | | |
|-----------------------------|----------------------|---------------|
| MODULUS OF ELASTICITY (PSI) | EP,EG = 30,000,000. | 30,000,000. |
| POISSON'S RATIO | MU(P),MU(G) = 0.3000 | 0.3000 |
| BRINELL HARDNESS | HBP,HBG = 654 | 654 |
| MATERIAL (CODE) | = STEEL(1) | STEEL(1) |
| MATERIAL GRADE | = 2 | 2 |
| HEAT-TREATMENT (CODE) | = CARBURIZED(4) | CARBURIZED(4) |

LOAD DATA

| | | |
|-----------------------------------|-------------------|---|
| TRANSMITTED POWER (HP) | P = 194.8517 | |
| PINION SPEED (rpm) | n(P) = 1,569.2330 | |
| GEAR BLANK TEMPERATURE (DEG. F) | Tb = 185. | |
| RELIABILITY | R = 0.9900 | |
| NUMBER OF CONTACTS PER REVOLUTION | = 3 | 1 |
| REVERSED BENDING? | = N | Y |
| SPUR GEAR LOADING TYPE | = HPSTC (1) | |

DERATING FACTORS

| | |
|--|-------------|
| APPLICATION FACTOR FOR PITTING RESIST. | Ca = 1.0000 |
| SIZE FACTOR FOR PITTING RESISTANCE | Cs = 1.0000 |
| SURFACE CONDITION FACTOR | Cf = 1.0000 |
| LOAD DIST. FACTOR FOR PITTING RESIST. | Cm = 1.3000 |
| DYNAMIC FACTOR FOR PITTING RESISTANCE | Cv = 0.9060 |

RUNTIME OPTIONS

| | |
|-----------------------------|----------------|
| TYPE OF ANALYSIS CHOSEN | = MINER'S RULE |
| CURVE CHOSEN, FIGS. 20 & 21 | = LOWER |

*****GEOMETRY SUMMARY-1*****

| | | PINION | GEAR |
|----------------------|----------|--------|---------|
| GENERATING PITCH DIA | ds, Ds = | 4.7244 | 13.7008 |
| OPERATING PITCH DIA | d, D = | 4.8254 | 13.9935 |
| BASE DIA | db, Db = | 4.4395 | 12.8745 |
| MEAN DIA of PINION | dm = | 4.9319 | |

PRESSURE ANGLES

| | | |
|----------------------|----------|---------|
| STANDARD TRANSVERSE | PHI(s) = | 20.0000 |
| OPERATING TRANSVERSE | PHI(t) = | 23.0690 |
| STANDARD NORMAL | PHI(c) = | 20.0000 |
| OPERATING NORMAL | PHI(n) = | 23.0690 |

HELIX ANGLES

| | | |
|-----------|----------|--------|
| STANDARD | PSI(s) = | 0.0000 |
| OPERATING | PSI = | 0.0000 |
| BASE | PSI(b) = | 0.0000 |

PITCHES

| | | |
|----------------------|------|--------|
| TRANSVERSE DIAMETRAL | Pd = | 4.2333 |
| TRANSVERSE BASE | pb = | 0.6974 |
| NORMAL BASE | pN = | 0.6974 |
| AXIAL | px = | 0.0000 |

DISTANCES ALONG LINE OF ACTION (FIG. 1)

| | | |
|---------------------------------------|------|--------|
| ACTIVE LENGTH OF LINE OF ACTION | Z = | 0.9296 |
| PINION ADDENDUM PORTION OF Z | Za = | 0.5501 |
| PINION DEDENDUM PORTION OF Z | Zb = | 0.3795 |
| DIST. FROM PITCH POINT TO STRESS CALC | Zc = | 0.1473 |

RATIOS

| | | |
|------------------------------|------|--------|
| GEAR | mG = | 2.9000 |
| TRANSVERSE (PROFILE) CONTACT | mp = | 1.3330 |
| AXIAL (FACE) CONTACT | mF = | 0.0000 |
| LOAD SHARING (mN = F/Lmin) | mN = | 1.0000 |

TRANSVERSE RADII OF CURVATURE

| | | |
|------------------------------------|------|--------|
| AT OPERATING PITCH POINT OF PINION | RP = | 0.9454 |
| AT OPERATING PITCH POINT OF GEAR | RG = | 2.7416 |
| AT POINT OF STRESS CALC OF PINION | R1 = | 0.7981 |
| AT POINT OF STRESS CALC OF GEAR | R2 = | 2.8889 |

NOTE: All dims in inches, all angles in degrees.

*****GEOMETRY SUMMARY-2*****

PITTING RESISTANCE GEOMETRY FACTOR DATA

| | | |
|------------------------------------|----------|--------|
| GEAR RATIO FACTOR | CG = | 0.7436 |
| CURVATURE FACTOR | Cc = | 0.1340 |
| CONTACT HEIGHT FACTOR | Cx = | 0.8896 |
| CONTACT HEIGHT FACTOR (LCR) | Cxh = | 1.0828 |
| HELICAL OVERLAP FACTOR | C(PSI) = | 1.0000 |
| MINIMUM LENGTH OF CONTACT | Lmin = | 3.1496 |
| PITTING RESISTANCE GEOMETRY FACTOR | I = | 0.1192 |

BENDING STRENGTH GEOMETRY FACTOR DATA

| | | PINION | GEAR |
|-------------------------------------|----------|--------|--------|
| LOAD ANGLE | PHI(L) = | 0.4602 | 0.4016 |
| HEIGHT OF LEWIS PARABOLA | h = | 1.2902 | 1.3648 |
| TOOTH THICKNESS AT CRITICAL SECTION | t = | 2.1153 | 2.2804 |
| HELICAL FACTOR | Ch = | 1.0000 | 1.0000 |
| HELIX ANGLE FACTOR | K(PSI) = | 1.0000 | 1.0000 |
| STRESS CORRECTION FACTOR | Kf = | 1.7656 | 1.8088 |
| TOOTH FORM FACTOR | Y = | 0.6866 | 0.7199 |
| BENDING STRENGTH GEOMETRY FACTOR | J = | 0.3888 | 0.3980 |

*****LOAD SUMMARY*****

| | | |
|---|--------|-----------|
| PITCH LINE VELOCITY (FPM) | vt = | 1,982. |
| TRANSMITTED TANGENTIAL LOAD (LB.) | Wt = | 3,244. |
| TORQUE TRANSMITTED BY PINION (LB.IN.) | T(1) = | 7.83D+003 |
| TORQUE TRANSMITTED BY GEAR (LB.IN.) | T(2) = | 2.27D+004 |
| CONTACT LOAD FACTOR FOR PITTING RESIST. | K = | 287. |
| UNIT LOAD FACTOR FOR BENDING STRENGTH | U(L) = | 4,360. |

*****DERATING FACTOR SUMMARY*****

| | | |
|------------------------------|----------|--------|
| APPLICATION | Ca, Ka = | 1.0000 |
| SIZE | Cs, Ks = | 1.0000 |
| LOAD DISTRIBUTION | Cm, Km = | 1.3000 |
| DYNAMIC | Cv, Kv = | 0.9060 |
| SURFACE CONDITION | Cf = | 1.0000 |
| COMBINED DURABILITY DERATING | C(D) = | 1.4349 |
| COMBINED STRENGTH DERATING | K(D) = | 1.4349 |

NOTE: Transverse Load Distribution Factor Cmt = 1.0

=====
STRENGTH SUMMARY
=====

| | | |
|--|-------------|--------------|
| HARDNESS RATIO FACTOR | C(H) = | 1.0000 |
| TEMPERATURE FACTOR | C(T),K(T) = | 1.0000 |
| RELIABILITY FACTOR | C(R),K(R) = | 1.0000 |
| ALLOW. CONTACT STRESS NO.,PINION (PSI) | Sac1 = | 225,000. *a* |
| ALLOW. CONTACT STRESS NO.,GEAR (PSI) | Sac2 = | 225,000. *a* |
| ALLOW. BENDING STRESS NO.,PINION (PSI) | Sat1 = | 70,000. *a* |
| ALLOW. BENDING STRESS NO.,GEAR (PSI) | Sat2 = | 49,000. *a* |

a NOTE: Based on allowable stresses at 10^7 cycles to failure.
with effects of C(H), C(T), & C(R).

=====
STRESS SUMMARY
=====

| | | |
|---------------------------------|-------|----------|
| ELASTIC COEFFICIENT | Cp = | 2,291. |
| CONTACT STRESS NO. (PSI) | Sc = | 116,088. |
| PINION BENDING STRESS NO. (PSI) | St1 = | 16,088. |
| GEAR BENDING STRESS NO. (PSI) | St2 = | 15,717. |

=====
HERTZIAN LIFE
PINION
=====

| CASE IDENT: | WTC HS/SP | | | |
|--------------|----------------------|-----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 86943. | 2.37D+014 | 2.40D-003 |
| .605312 | .033566 | 90318. | 1.20D+014 | 3.64D-004 |
| .64971 | .033172 | 93572. | 6.37D+013 | 6.78D-004 |
| .694108 | .032133 | 96716. | 3.53D+013 | 1.18D-003 |
| .738506 | .03127 | 99762. | 2.03D+013 | 2.00D-003 |
| .782904 | .030523 | 102717. | 1.20D+013 | 3.30D-003 |
| .827302 | .029989 | 105589. | 7.36D+012 | 5.30D-003 |
| .871699 | .031354 | 108385. | 4.62D+012 | 8.83D-003 |
| .916097 | .034356 | 111111. | 2.96D+012 | 1.51D-002 |
| .960495 | .038603 | 113772. | 1.94D+012 | 2.59D-002 |
| .982694 | .020871 | 115079. | 1.58D+012 | 1.71D-002 |
| 1.00489 | .022409 | 116371. | 1.30D+012 | 2.25D-002 |
| 1.02709 | .023481 | 117650. | 1.07D+012 | 2.86D-002 |
| 1.04929 | .023909 | 118914. | 8.82D+011 | 3.53D-002 |
| 1.07149 | .023918 | 120166. | 7.31D+011 | 4.25D-002 |
| 1.09369 | .023435 | 121404. | 6.09D+011 | 5.01D-002 |
| 1.11589 | .022204 | 122630. | 5.09D+011 | 5.67D-002 |
| 1.13809 | .020372 | 123844. | 4.27D+011 | 6.21D-002 |
| 1.16029 | .018423 | 125046. | 3.59D+011 | 6.67D-002 |
| 1.18248 | .015961 | 126236. | 3.03D+011 | 6.84D-002 |
| 1.20468 | .013135 | 127415. | 2.57D+011 | 6.65D-002 |
| 1.22688 | .010582 | 128584. | 2.18D+011 | 6.31D-002 |
| 1.24908 | .008399 | 129742. | 1.86D+011 | 5.87D-002 |
| 1.27128 | .006331 | 130890. | 1.59D+011 | 5.18D-002 |
| 1.29348 | .004665 | 132028. | 1.36D+011 | 4.46D-002 |
| 1.31568 | .003331 | 133156. | 1.17D+011 | 3.70D-002 |
| 1.33788 | .002398 | 134275. | 1.01D+011 | 3.10D-002 |
| 1.36008 | .00173 | 135384. | 8.70D+010 | 2.59D-002 |
| 1.38227 | .001197 | 136484. | 7.53D+010 | 2.07D-002 |
| 1.40447 | .000818 | 137576. | 6.53D+010 | 1.63D-002 |
| 1.42667 | .000529 | 138659. | 5.68D+010 | 1.21D-002 |
| 1.44887 | .000391 | 139734. | 4.95D+010 | 1.03D-002 |
| 1.47107 | .000246 | 140800. | 4.32D+010 | 7.41D-003 |
| 1.49327 | .000157 | 141859. | 3.78D+010 | 5.41D-003 |
| 1.53767 | .00021 | 143952. | 2.91D+010 | 9.40D-003 |
| 1.58207 | .000098 | 146016. | 2.26D+010 | 5.65D-003 |
| 1.62646 | .000052 | 148050. | 1.76D+010 | 3.84D-003 |
| 1.67086 | .000028 | 150057. | 1.38D+010 | 2.63D-003 |
| 1.71526 | .000018 | 152038. | 1.10D+010 | 2.14D-003 |
| 1.75966 | .000016 | 153993. | 8.72D+009 | 2.39D-003 |
| 1.80406 | .000007 | 155924. | 6.98D+009 | 1.30D-003 |
| 1.84845 | .000004 | 157830. | 5.62D+009 | 9.26D-004 |
| 1.89285 | .000001 | 159715. | 4.55D+009 | 2.86D-004 |

GEARTECH
CASE IDENT: WTC HS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 6

=====
HERTZIAN LIFE
PINION (Continued)
=====

| CASE IDENT: | WTC HS/SP | | | |
|--------------|----------------------|-----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| 1.93725 | 7.6E-07 | 161577. | 3.70D+009 | 2.67D-004 |
| 1.98165 | 9.8E-07 | 163418. | 3.02D+009 | 4.22D-004 |
| 2.04824 | 5.8E-07 | 166141. | 2.25D+009 | 3.36D-004 |
| 2.11484 | 7.9E-07 | 168820. | 1.69D+009 | 6.08D-004 |
| 2.15924 | .000002 | 170583. | 1.40D+009 | 1.85D-003 |
| 2.20364 | 7.8E-07 | 172328. | 1.17D+009 | 8.67D-004 |
| 2.35903 | .0000006 | 178301. | 6.37D+008 | 1.23D-003 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE HERTZIAN STRESS Sc = 1.16D+005
RESULTANT HERTZIAN LIFE Nc = 1.30D+012 CYCLES
RESULTANT HERTZIAN LIFE Nc = 4.61D+006 HOURS

=====
****BENDING LIFE****
PINION
=====

| CASE IDENT: | WTC HS/SP | | | |
|--------------|----------------------|----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 9024. | 3.51D+034 | 2.42D-014 |
| .605312 | .033566 | 9738. | 3.32D+033 | 1.97D-014 |
| .64971 | .033172 | 10453. | 3.71D+032 | 1.74D-013 |
| .694108 | .032133 | 11167. | 4.79D+031 | 1.31D-012 |
| .738506 | .03127 | 11881. | 7.03D+030 | 8.67D-012 |
| .782904 | .030523 | 12595. | 1.15D+030 | 5.16D-011 |
| .827302 | .029989 | 13310. | 2.09D+029 | 2.79D-010 |
| .871699 | .031354 | 14024. | 4.14D+028 | 1.47D-009 |
| .916097 | .034356 | 14738. | 8.90D+027 | 7.52D-009 |
| .960495 | .038603 | 15452. | 2.06D+027 | 3.66D-008 |
| .982694 | .020871 | 15810. | 1.01D+027 | 4.01D-008 |
| 1.00489 | .022409 | 16167. | 5.08D+026 | 8.60D-008 |
| 1.02709 | .023481 | 16524. | 2.58D+026 | 1.77D-007 |
| 1.04929 | .023909 | 16881. | 1.33D+026 | 3.50D-007 |
| 1.07149 | .023918 | 17238. | 6.96D+025 | 6.69D-007 |
| 1.09369 | .023435 | 17595. | 3.69D+025 | 1.24D-006 |
| 1.11589 | .022204 | 17952. | 1.98D+025 | 2.18D-006 |
| 1.13809 | .020372 | 18310. | 1.08D+025 | 3.69D-006 |
| 1.16029 | .018423 | 18667. | 5.92D+024 | 6.06D-006 |
| 1.18248 | .015961 | 19024. | 3.29D+024 | 9.44D-006 |
| 1.20468 | .013135 | 19381. | 1.85D+024 | 1.38D-005 |
| 1.22688 | .010582 | 19738. | 1.05D+024 | 1.96D-005 |
| 1.24908 | .008399 | 20095. | 6.03D+023 | 2.71D-005 |
| 1.27128 | .006331 | 20452. | 3.50D+023 | 3.53D-005 |
| 1.29348 | .004665 | 20810. | 2.05D+023 | 4.44D-005 |
| 1.31568 | .003331 | 21167. | 1.21D+023 | 5.37D-005 |
| 1.33788 | .002398 | 21524. | 7.20D+022 | 6.49D-005 |
| 1.36008 | .00173 | 21881. | 4.32D+022 | 7.79D-005 |
| 1.38227 | .001197 | 22238. | 2.62D+022 | 8.90D-005 |
| 1.40447 | .000818 | 22595. | 1.60D+022 | 9.96D-005 |
| 1.42667 | .000529 | 22952. | 9.85D+021 | 1.05D-004 |
| 1.44887 | .000391 | 23309. | 6.10D+021 | 1.25D-004 |
| 1.47107 | .000246 | 23667. | 3.81D+021 | 1.26D-004 |
| 1.49327 | .000157 | 24024. | 2.40D+021 | 1.28D-004 |
| 1.53767 | .00021 | 24738. | 9.68D+020 | 4.23D-004 |
| 1.58207 | .000098 | 25452. | 4.01D+020 | 4.76D-004 |
| 1.62646 | .000052 | 26167. | 1.70D+020 | 5.95D-004 |
| 1.67086 | .000028 | 26881. | 7.39D+019 | 7.38D-004 |
| 1.71526 | .000018 | 27595. | 3.28D+019 | 1.07D-003 |
| 1.75966 | .000016 | 28309. | 1.49D+019 | 2.09D-003 |
| 1.80406 | .000007 | 29024. | 6.88D+018 | 1.98D-003 |
| 1.84845 | .000004 | 29738. | 3.24D+018 | 2.40D-003 |
| 1.89285 | .000001 | 30452. | 1.55D+018 | 1.25D-003 |

GEARTECH
CASE IDENT: WTC HS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 8

=====
****BENDING LIFE****
PINION (Continued)
=====

| CASE IDENT: | WTC HS/SP | | | |
|--------------|----------------------|----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| 1.93725 | 7.6E-07 | 31167. | 7.58D+017 | 1.95D-003 |
| 1.98165 | 9.8E-07 | 31881. | 3.76D+017 | 5.08D-003 |
| 2.04824 | 5.8E-07 | 32952. | 1.35D+017 | 8.36D-003 |
| 2.11484 | 7.9E-07 | 34024. | 5.02D+016 | 3.07D-002 |
| 2.15924 | .000002 | 34738. | 2.64D+016 | 1.48D-001 |
| 2.20364 | 7.8E-07 | 35452. | 1.40D+016 | 1.08D-001 |
| 2.35903 | .0000006 | 37952. | 1.70D+015 | 6.86D-001 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE BENDING STRESS St = 1.61D+004
RESULTANT BENDING LIFE Nt = 1.95D+021 CYCLES
RESULTANT BENDING LIFE Nt = 6.90D+015 HOURS

=====
HERTZIAN LIFE
GEAR
=====

| CASE IDENT: | WTC HS/SP | | | |
|--------------|----------------------|-----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 86943. | 2.37D+014 | 2.40D-003 |
| .605312 | .033566 | 90318. | 1.20D+014 | 3.64D-004 |
| .64971 | .033172 | 93572. | 6.37D+013 | 6.78D-004 |
| .694108 | .032133 | 96716. | 3.53D+013 | 1.18D-003 |
| .738506 | .03127 | 99762. | 2.03D+013 | 2.00D-003 |
| .782904 | .030523 | 102717. | 1.20D+013 | 3.30D-003 |
| .827302 | .029989 | 105589. | 7.36D+012 | 5.30D-003 |
| .871699 | .031354 | 108385. | 4.62D+012 | 8.83D-003 |
| .916097 | .034356 | 111111. | 2.96D+012 | 1.51D-002 |
| .960495 | .038603 | 113772. | 1.94D+012 | 2.59D-002 |
| .982694 | .020871 | 115079. | 1.58D+012 | 1.71D-002 |
| 1.00489 | .022409 | 116371. | 1.30D+012 | 2.25D-002 |
| 1.02709 | .023481 | 117650. | 1.07D+012 | 2.86D-002 |
| 1.04929 | .023909 | 118914. | 8.82D+011 | 3.53D-002 |
| 1.07149 | .023918 | 120166. | 7.31D+011 | 4.25D-002 |
| 1.09369 | .023435 | 121404. | 6.09D+011 | 5.01D-002 |
| 1.11589 | .022204 | 122630. | 5.09D+011 | 5.67D-002 |
| 1.13809 | .020372 | 123844. | 4.27D+011 | 6.21D-002 |
| 1.16029 | .018423 | 125046. | 3.59D+011 | 6.67D-002 |
| 1.18248 | .015961 | 126236. | 3.03D+011 | 6.84D-002 |
| 1.20468 | .013135 | 127415. | 2.57D+011 | 6.65D-002 |
| 1.22688 | .010582 | 128584. | 2.18D+011 | 6.31D-002 |
| 1.24908 | .008399 | 129742. | 1.86D+011 | 5.87D-002 |
| 1.27128 | .006331 | 130890. | 1.59D+011 | 5.18D-002 |
| 1.29348 | .004665 | 132028. | 1.36D+011 | 4.46D-002 |
| 1.31568 | .003331 | 133156. | 1.17D+011 | 3.70D-002 |
| 1.33788 | .002398 | 134275. | 1.01D+011 | 3.10D-002 |
| 1.36008 | .00173 | 135384. | 8.70D+010 | 2.59D-002 |
| 1.38227 | .001197 | 136484. | 7.53D+010 | 2.07D-002 |
| 1.40447 | .000818 | 137576. | 6.53D+010 | 1.63D-002 |
| 1.42667 | .000529 | 138659. | 5.68D+010 | 1.21D-002 |
| 1.44887 | .000391 | 139734. | 4.95D+010 | 1.03D-002 |
| 1.47107 | .000246 | 140800. | 4.32D+010 | 7.41D-003 |
| 1.49327 | .000157 | 141859. | 3.78D+010 | 5.41D-003 |
| 1.53767 | .00021 | 143952. | 2.91D+010 | 9.40D-003 |
| 1.58207 | .000098 | 146016. | 2.26D+010 | 5.65D-003 |
| 1.62646 | .000052 | 148050. | 1.76D+010 | 3.84D-003 |
| 1.67086 | .000028 | 150057. | 1.38D+010 | 2.63D-003 |
| 1.71526 | .000018 | 152038. | 1.10D+010 | 2.14D-003 |
| 1.75966 | .000016 | 153993. | 8.72D+009 | 2.39D-003 |
| 1.80406 | .000007 | 155924. | 6.98D+009 | 1.30D-003 |
| 1.84845 | .000004 | 157830. | 5.62D+009 | 9.26D-004 |
| 1.89285 | .000001 | 159715. | 4.55D+009 | 2.86D-004 |

GEARTECH
CASE IDENT: WTC HS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 10

=====
HERTZIAN LIFE
GEAR (Continued)
=====

| LOAD RATIO | CYCLE RATIO | HERTZIAN STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
|------------|-------------|-----------------|-------------------|--------------|
| 1.93725 | 7.6E-07 | 161577. | 3.70D+009 | 2.67D-004 |
| 1.98165 | 9.8E-07 | 163418. | 3.02D+009 | 4.22D-004 |
| 2.04824 | 5.8E-07 | 166141. | 2.25D+009 | 3.36D-004 |
| 2.11484 | 7.9E-07 | 168820. | 1.69D+009 | 6.08D-004 |
| 2.15924 | .000002 | 170583. | 1.40D+009 | 1.85D-003 |
| 2.20364 | 7.8E-07 | 172328. | 1.17D+009 | 8.67D-004 |
| 2.35903 | .0000006 | 178301. | 6.37D+008 | 1.23D-003 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE HERTZIAN STRESS $S_c = 1.16D+005$
RESULTANT HERTZIAN LIFE $N_c = 1.30D+012$ CYCLES
RESULTANT HERTZIAN LIFE $N_c = 4.01D+007$ HOURS

=====
****BENDING LIFE****
GEAR
=====

| CASE IDENT: | WTC HS/SP | | | |
|--------------|----------------------|----------------|-------------------|--------------|
| ARRAY IDENT: | EMD-1 wind loads 5th | | | |
| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
| .560914 | .435701 | 8816. | 1.16D+030 | 2.42D-014 |
| .605312 | .033566 | 9514. | 1.09D+029 | 1.97D-014 |
| .64971 | .033172 | 10211. | 1.22D+028 | 1.74D-013 |
| .694108 | .032133 | 10909. | 1.58D+027 | 1.31D-012 |
| .738506 | .03127 | 11607. | 2.32D+026 | 8.67D-012 |
| .782904 | .030523 | 12305. | 3.80D+025 | 5.16D-011 |
| .827302 | .029989 | 13003. | 6.89D+024 | 2.79D-010 |
| .871699 | .031354 | 13700. | 1.37D+024 | 1.47D-009 |
| .916097 | .034356 | 14398. | 2.93D+023 | 7.52D-009 |
| .960495 | .038603 | 15096. | 6.78D+022 | 3.66D-008 |
| .982694 | .020871 | 15445. | 3.34D+022 | 4.01D-008 |
| 1.00489 | .022409 | 15794. | 1.67D+022 | 8.60D-008 |
| 1.02709 | .023481 | 16143. | 8.51D+021 | 1.77D-007 |
| 1.04929 | .023909 | 16492. | 4.39D+021 | 3.50D-007 |
| 1.07149 | .023918 | 16840. | 2.29D+021 | 6.69D-007 |
| 1.09369 | .023435 | 17189. | 1.22D+021 | 1.24D-006 |
| 1.11589 | .022204 | 17538. | 6.53D+020 | 2.18D-006 |
| 1.13809 | .020372 | 17887. | 3.55D+020 | 3.69D-006 |
| 1.16029 | .018423 | 18236. | 1.95D+020 | 6.06D-006 |
| 1.18248 | .015961 | 18585. | 1.09D+020 | 9.44D-006 |
| 1.20468 | .013135 | 18934. | 6.10D+019 | 1.38D-005 |
| 1.22688 | .010582 | 19283. | 3.47D+019 | 1.96D-005 |
| 1.24908 | .008399 | 19632. | 1.99D+019 | 2.71D-005 |
| 1.27128 | .006331 | 19981. | 1.15D+019 | 3.53D-005 |
| 1.29348 | .004665 | 20329. | 6.75D+018 | 4.44D-005 |
| 1.31568 | .003331 | 20678. | 3.98D+018 | 5.37D-005 |
| 1.33788 | .002398 | 21027. | 2.37D+018 | 6.49D-005 |
| 1.36008 | .00173 | 21376. | 1.43D+018 | 7.79D-005 |
| 1.38227 | .001197 | 21725. | 8.64D+017 | 8.90D-005 |
| 1.40447 | .000818 | 22074. | 5.27D+017 | 9.96D-005 |
| 1.42667 | .000529 | 22423. | 3.25D+017 | 1.05D-004 |
| 1.44887 | .000391 | 22772. | 2.01D+017 | 1.25D-004 |
| 1.47107 | .000246 | 23121. | 1.26D+017 | 1.26D-004 |
| 1.49327 | .000157 | 23470. | 7.90D+016 | 1.28D-004 |
| 1.53767 | .00021 | 24167. | 3.19D+016 | 4.23D-004 |
| 1.58207 | .000098 | 24865. | 1.32D+016 | 4.76D-004 |
| 1.62646 | .000052 | 25563. | 5.61D+015 | 5.95D-004 |
| 1.67086 | .000028 | 26261. | 2.44D+015 | 7.38D-004 |
| 1.71526 | .000018 | 26959. | 1.08D+015 | 1.07D-003 |
| 1.75966 | .000016 | 27656. | 4.91D+014 | 2.09D-003 |
| 1.80406 | .000007 | 28354. | 2.27D+014 | 1.98D-003 |
| 1.84845 | .000004 | 29052. | 1.07D+014 | 2.40D-003 |
| 1.89285 | .000001 | 29750. | 5.13D+013 | 1.25D-003 |

GEARTECH
CASE IDENT: WTC HS/SP
PROGRAM AGMA218 v.1.06B

ANALYST: RLE

DATE: 06-13-02

ANALYSIS OPTION: MINER'S RULE PAGE: 12

=====
****BENDING LIFE****
GEAR (Continued)
=====

| LOAD RATIO | CYCLE RATIO | BENDING STRESS | CYCLES TO FAILURE | DAMAGE RATIO |
|------------|-------------|----------------|-------------------|--------------|
| 1.93725 | 7.6E-07 | 30447. | 2.50D+013 | 1.95D-003 |
| 1.98165 | 9.8E-07 | 31145. | 1.24D+013 | 5.08D-003 |
| 2.04824 | 5.8E-07 | 32192. | 4.46D+012 | 8.36D-003 |
| 2.11484 | 7.9E-07 | 33239. | 1.65D+012 | 3.07D-002 |
| 2.15924 | .000002 | 33936. | 8.70D+011 | 1.48D-001 |
| 2.20364 | 7.8E-07 | 34634. | 4.63D+011 | 1.08D-001 |
| 2.35903 | .0000006 | 37077. | 5.62D+010 | 6.86D-001 |
| ----- | | | | |
| | 1.0000 | | | 1.0000 |

BASELINE BENDING STRESS St = 1.57D+004
RESULTANT BENDING LIFE Nt = 6.42D+016 CYCLES
RESULTANT BENDING LIFE Nt = 1.98D+012 HOURS

*****INPUT DATA SUMMARY*****

GEAR GEOMETRY DATA

| | | PINION | GEAR |
|---------------------------------|----------|---------|---------|
| TOOTH NUMBER | NP,NG = | 17. | 49. |
| NET FACE WIDTH (in.) | F1,F2 = | 5.7087 | 5.7087 |
| OUTSIDE DIAMETER (in.) | do,Do = | 6.9590 | 18.2960 |
| INTERNAL GEAR I.D. (in.) | Di = | | 0.0000 |
| NORMAL DIAMETRAL PITCH | Pnd = | 2.8222 | |
| NORMAL PRESSURE ANGLE (deg.) | PHI(c) = | 20.0000 | |
| STANDARD HELIX ANGLE (deg.) | PSI(s) = | 0.0000 | |
| OPERATING CENTER DISTANCE (in.) | C = | 11.9685 | |

GEAR GEOMETRY DATA FOR Pnd = 1.0

| | | | |
|---|---------|--------|--------|
| ADDENDUM MODIFICATION COEFFICIENT | X1,X2 = | 0.4600 | 0.3819 |
| THINNING FOR BACKLASH DELTA(sn1),DELTA(sn2) | = | 0.0298 | 0.0056 |
| STOCK ALLOW. PER SIDE FOR FINISHING Us1,Us2 | = | 0.0261 | 0.0261 |

TOOL GEOMETRY DATA FOR Pnd = 1.0

| | | | |
|---------------------------------------|-------------|--------|--------|
| TOOL NORMAL TOOTH THICKNESS | tce1,tce2 = | 1.5185 | 1.5185 |
| TOOL ADDENDUM | hao1,hao2 = | 1.4000 | 1.4000 |
| TOOL TIP RADIUS | rTe1,rTe2 = | 0.4000 | 0.4000 |
| TOOL PROTUBERANCE DELTA(o1),DELTA(o2) | = | 0.0361 | 0.0361 |

MATERIALS/LUBE DATA

| | | | |
|-----------------------------------|---------------|---------------|---------------|
| MODULUS OF ELASTICITY (lb/in^2) | EP,EG = | 3.00D+007 | 3.00D+007 |
| POISSON'S RATIO | MU(P),MU(G) = | 0.3000 | 0.3000 |
| HEAT-TREATMENT (CODE) | = | CARBURIZED(4) | CARBURIZED(4) |
| SURFACE ROUGHNESS (micro-in, rms) | = | 20. | 20. |
| LUBRICANT TYPE (CODE) | = | MINERAL (2) | |
| GEAR BULK TEMPERATURE (deg. F) | Tb = | 185. | |
| LUBE ABSOLUTE VISCOSITY (cP) | ETA(o) = | 10.500 | |
| PRESS-VISCOSITY COEFF. (in^2/lb.) | ALPHA = | 9.91E-005 | |
| MEAN CRITICAL TOTAL TEMP (deg. F) | = | 482. | |
| STANDARD DEVIATION (deg. F) | = | 72.00 | |

LOAD DATA

| | | |
|------------------------|--------|----------|
| TRANSMITTED POWER (HP) | P = | 194.7195 |
| PINION SPEED (rpm) | n(P) = | 201.0471 |

DERATING FACTORS

| | | |
|-------------------|------|--------|
| APPLICATION | Ca = | 2.3600 |
| LOAD DISTRIBUTION | Cm = | 1.0700 |
| DYNAMIC | Cv = | 0.9560 |

ANALYSIS OPTIONS

| | | |
|--|---|----------|
| NO. OF POINTS ALONG PROFILE CALCULATED | = | 25 |
| DRIVING MEMBER (CODE) | = | GEAR (2) |

MODIFIED PROFILES? (CODE)
COEFF. OF FRICTION OPTION

= MODIFIED (1)
= CONSTANT f = .06

=====
GEOMETRY SUMMARY-1
=====

CENTER DISTANCE

| | | |
|-----------|----------|---------|
| STANDARD | C(std) = | 11.6929 |
| OPERATING | C = | 11.9685 |

TRANSVERSE PRESSURE ANGLES

| | | |
|-----------------------|----------|---------|
| STANDARD (GENERATING) | PHI(s) = | 20.0000 |
| OPERATING | PHI(t) = | 23.3566 |

NORMAL PRESSURE ANGLES

| | | |
|-----------------------|----------|---------|
| STANDARD (GENERATING) | PHI(c) = | 20.0000 |
| OPERATING | PHI(n) = | 23.3566 |

HELIX ANGLES

| | | |
|-----------------------|----------|--------|
| STANDARD (GENERATING) | PSI(s) = | 0.0000 |
| OPERATING | PSI = | 0.0000 |
| BASE | PSI(b) = | 0.0000 |

PITCHES

| | | |
|----------------------|------|--------|
| TRANSVERSE DIAMETRAL | Pd = | 2.8222 |
| TRANSVERSE CIRCULAR | p = | 1.1132 |
| NORMAL CIRCULAR | pn = | 1.1132 |
| TRANSVERSE BASE | pb = | 1.0460 |
| NORMAL BASE | pN = | 1.0460 |
| AXIAL | px = | 0.0000 |

DISTANCES ALONG LINE OF ACTION

| | | |
|--------------------------------------|------|--------|
| START OF ACTIVE PROFILE (SAP) | C1 = | 0.6049 |
| LOW SINGLE TOOTH CONTACT (LPSTC) | C2 = | 0.9781 |
| PITCH POINT | C3 = | 1.2222 |
| HIGH SINGLE TOOTH CONTACT (HPSTC) | C4 = | 1.6509 |
| END OF ACTIVE PROFILE (EAP) | C5 = | 2.0241 |
| DISTANCE BETWEEN INTERFERENCE POINTS | C6 = | 4.7449 |
| ACTIVE LENGTH OF LINE OF ACTION | Z = | 1.4192 |
| PINION ADDENDUM PORTION OF Z | Za = | 0.8019 |
| PINION DEDENDUM PORTION OF Z | Zb = | 0.6173 |

LENGTH OF CONTACT LINE

| | | |
|---------|--------|---------|
| MINIMUM | Lmin = | 5.7087 |
| MAXIMUM | Lmax = | 11.4174 |
| AVERAGE | Lavg = | 8.5631 |

*****GEOMETRY SUMMARY-2*****

RATIOS

| | | |
|------------------------------|-------|--------|
| CONTACT LENGTH | mL = | 2.0000 |
| TRANSVERSE (PROFILE) CONTACT | mp = | 1.3568 |
| AXIAL (FACE) CONTACT | mF = | 0.0000 |
| TOTAL CONTACT | mt = | 1.3568 |
| GEAR | mG = | 2.8824 |
| LOAD SHARING | mN = | 1.0000 |
| LOAD SHARING | mNa = | 1.0000 |

DIAMETERS

| | | PINION | GEAR |
|------------------|---------|--------|---------|
| POINTED TEETH | dp,Dp = | 7.2487 | 18.7989 |
| OPERATING PITCH | d,D = | 6.1656 | 17.7714 |
| GENERATING PITCH | ds,Ds = | 6.0236 | 17.3622 |
| LIMIT (SAP) | dc,Dc = | 5.7882 | 17.1987 |
| TOP OF FILLET | de,De = | 5.7050 | 16.9237 |
| BASE | db,Db = | 5.6604 | 16.3151 |
| ROOT | dR,DR = | 5.3285 | 16.6353 |

TOOTH DEPTHS

| | | | |
|---------------------|-----------|--------|--------|
| OPERATING ADDENDA | a1,a2 = | 0.3967 | 0.2623 |
| OPERATING DEDENDA | b1,b2 = | 0.4186 | 0.5681 |
| OPERATING CLEARANCE | c1,c2 = | 0.1714 | 0.1563 |
| WHOLE DEPTH | ht1,ht2 = | 0.8153 | 0.8304 |
| WORKING DEPTH | hK = | 0.6590 | |

TRANSVERSE CIRCULAR TOOTH THICKNESSES

| | | | |
|------------|-----------|--------|--------|
| TOPLAND | to1,to2 = | 0.2151 | 0.2680 |
| OPERATING | tr1,tr2 = | 0.6231 | 0.5035 |
| GENERATING | tg1,tg2 = | 0.6647 | 0.6531 |
| BASE | tb1,tb2 = | 0.7090 | 0.8569 |

NORMAL CIRCULAR TOOTH THICKNESSES

| | | | |
|------------|-------------|--------|--------|
| TOPLAND | tno1,tno2 = | 0.2151 | 0.2680 |
| OPERATING | tnr1,tnr2 = | 0.6231 | 0.5035 |
| GENERATING | tng1,tng2 = | 0.6647 | 0.6531 |
| BASE | tnb1,tnb2 = | 0.7090 | 0.8569 |

| | | | |
|------|---------|--------|--------|
| LEAD | L1,L2 = | 0.0000 | 0.0000 |
|------|---------|--------|--------|

OPERATING CIRCULAR BACKLASH

| | | |
|------------|------|--------|
| TRANSVERSE | B = | 0.0128 |
| NORMAL | Bn = | 0.0128 |

NOTE: All dims in inches, all angles in degrees.

=====
LOAD/DERATING FACTOR SUMMARY
=====

NOMINAL OPERATING LOADS

PINION TORQUE (lb.-in.) T1 = 6.10E+004
TANGENTIAL LOAD (lb.) (Wtr)nom = 1.98E+004

COMBINED DERATING FACTOR

C(D) = Ca Cm / Cv C(D) = 2.6414

ACTUAL OPERATING LOADS (includes C(D))

TANGENTIAL LOAD (lb.) Wtr = 5.23E+004
NORMAL LOAD (lb.) WNr = 5.70E+004
NORMAL UNIT LOAD (lb/in.) wNr = 9.98E+003

=====
MATERIALS/LUBE DATA SUMMARY
=====

MATERIAL DATA

REDUCED MODULUS (lb./in²) E' = 3.30E+007
EHD MATERIAL PARAMETER G = 3,267.0330
COMPOSITE SURFACE ROUGHNESS (micro-in) rms = 28.2843
AVERAGE SURFACE ROUGHNESS (micro-in) rms = 20.0000

LUBRICANT DATA

LUBRICANT TYPE (CODE) = MINERAL (2)
ABSOLUTE VISCOSITY (cP) ETA(o) = 1.05E+001
ABSOLUTE VISCOSITY (reyns) MU(o) = 1.52E-006
PRESSURE-VISCOSITY COEFF. (lb²/in.) ALPHA = 9.91E-005
GEAR BULK TEMPERATURE (deg. F) Tb = 185.0000

=====
RATING SUMMARY
=====

PITCHLINE VELOCITY (ft/min.) Vtr = 324.5205
APPROACH ACTION (%) = 56.50%
RECESS ACTION (%) = 43.50%
MAXIMUM SPECIFIC SLIDING RATIO Vss = -1.3745
MAXIMUM SLOPE = 12.7333
MAXIMUM HERTZIAN STRESS (lb/in²) qo = 259,684.
MAXIMUM TOTAL CONJUNCTION TEMP. (deg. F) Tc = 288.
MINIMUM FILM THICKNESS (micro-in) hmin = 2.2
MINIMUM SPECIFIC FILM THICKNESS LAMBDA = 0.078
PROBABILITY OF SCORING (%) Ps = < 5%
PROBABILITY OF WEAR (%) Pw = > 95%

=====
 ****Vss, hmin, Tc, etc. AT 5 REFERENCE POINTS****
 =====

| | Roll Angle (deg) | Rolling Velocity (in/s) | | Sliding Velocity (in/s) | | Entraining Velocity (in/s) | Specific Sliding Ratio | |
|----|------------------|-------------------------|-------|-------------------------|--------|----------------------------|------------------------|---------|
| | | Vr1 | Vr2 | Vs1 | Vs2 | | Ve | Vss1 |
| 1. | 12.25 | 12.74 | 30.24 | -17.51 | 17.51 | 42.98 | -1.3745 | 0.5789 |
| 2. | 19.80 | 20.59 | 27.51 | -6.92 | 6.92 | 48.11 | -0.3362 | 0.2516 |
| 3. | 24.74 | 25.73 | 25.73 | 0.00 | -0.00 | 51.46 | 0.0000 | -0.0000 |
| 4. | 33.42 | 34.76 | 22.60 | 12.16 | -12.16 | 57.36 | 0.3498 | -0.5380 |
| 5. | 40.98 | 42.61 | 19.87 | 22.74 | -22.74 | 62.49 | 0.5336 | -1.1443 |

| | Roll Angle (deg) | Hertzian Stress (lb/in ²) | Friction Coeff. | Flash T. Rise (deg F) | Total Temp (deg F) | EHD Film Thk (micro-in) | Specific Film Thk |
|----|------------------|---------------------------------------|-----------------|-----------------------|--------------------|-------------------------|-------------------|
| | | q | f | Tf | Tc | hmin | lambda |
| 1. | 12.25 | 119,068 | 0.060 | 48 | 233 | 2.3 | 0.082 |
| 2. | 19.80 | 259,684 | 0.060 | 69 | 254 | 2.3 | 0.082 |
| 3. | 24.74 | 240,222 | 0.060 | 0 | 185 | 2.6 | 0.091 |
| 4. | 33.42 | 220,545 | 0.060 | 103 | 288 | 3.0 | 0.106 |
| 5. | 40.98 | 0 | 0.060 | 0 | 185 | 0.0 | 0.000 |

| Roll Angle (deg) | -----Profile Radii of Curvature (inches)----- | | | | | Normal Relative rhon |
|------------------|---|------------|--------|--------|--------|----------------------|
| | epsilon | Transverse | | Normal | | |
| | rho1 | rho2 | rhon1 | rhon2 | | |
| 1. | 12.25 | 0.6049 | 4.1400 | 0.6049 | 4.1400 | 0.5278 |
| 2. | 19.80 | 0.9781 | 3.7669 | 0.9781 | 3.7669 | 0.7765 |
| 3. | 24.74 | 1.2222 | 3.5228 | 1.2222 | 3.5228 | 0.9074 |
| 4. | 33.42 | 1.6509 | 3.0940 | 1.6509 | 3.0940 | 1.0765 |
| 5. | 40.98 | 2.0241 | 2.7208 | 2.0241 | 2.7208 | 1.1607 |

- 1. = SAP: Start of Active Profile
- 2. = LPSTC: Lowest Point of Single Tooth Contact
- 3. = P: Pitch point
- 4. = HPSTC: Highest Point of Single Tooth Contact
- 5. = EAP: End of Active Profile

CASE IDENT: WTC HS/SP
SCORING+ v.1.03A

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*****INPUT DATA SUMMARY*****

GEAR GEOMETRY DATA

| | | PINION | GEAR |
|---------------------------------|----------|---------|---------|
| TOOTH NUMBER | NP,NG = | 20. | 58. |
| NET FACE WIDTH (in.) | F1,F2 = | 3.1496 | 3.1496 |
| OUTSIDE DIAMETER (in.) | do,Do = | 5.3530 | 14.3080 |
| INTERNAL GEAR I.D. (in.) | Di = | | 0.0000 |
| NORMAL DIAMETRAL PITCH | Pnd = | 4.2333 | |
| NORMAL PRESSURE ANGLE (deg.) | PHI(c) = | 20.0000 | |
| STANDARD HELIX ANGLE (deg.) | PSI(s) = | 0.0000 | |
| OPERATING CENTER DISTANCE (in.) | C = | 9.4094 | |

GEAR GEOMETRY DATA FOR Pnd = 1.0

| | | | |
|---|---------|--------|--------|
| ADDENDUM MODIFICATION COEFFICIENT | X1,X2 = | 0.4700 | 0.4260 |
| THINNING FOR BACKLASH DELTA(sn1),DELTA(sn2) | = | 0.0333 | 0.0083 |
| STOCK ALLOW. PER SIDE FOR FINISHING Us1,Us2 | = | 0.0343 | 0.0343 |

TOOL GEOMETRY DATA FOR Pnd = 1.0

| | | | |
|---------------------------------------|-------------|--------|--------|
| TOOL NORMAL TOOTH THICKNESS | tce1,tce2 = | 1.5023 | 1.5023 |
| TOOL ADDENDUM | hao1,hao2 = | 1.4000 | 1.4000 |
| TOOL TIP RADIUS | rTe1,rTe2 = | 0.4000 | 0.4000 |
| TOOL PROTUBERANCE DELTA(o1),DELTA(o2) | = | 0.0443 | 0.0443 |

MATERIALS/LUBE DATA

| | | | |
|-----------------------------------|---------------|---------------|---------------|
| MODULUS OF ELASTICITY (lb/in^2) | EP,EG = | 3.00D+007 | 3.00D+007 |
| POISSON'S RATIO | MU(P),MU(G) = | 0.3000 | 0.3000 |
| HEAT-TREATMENT (CODE) | = | CARBURIZED(4) | CARBURIZED(4) |
| SURFACE ROUGHNESS (micro-in, rms) | = | 20. | 20. |
| LUBRICANT TYPE (CODE) | = | MINERAL (2) | |
| GEAR BULK TEMPERATURE (deg. F) | Tb = | 185. | |
| LUBE ABSOLUTE VISCOSITY (cP) | ETA(o) = | 10.500 | |
| PRESS-VISCOSITY COEFF. (in^2/lb.) | ALPHA = | 9.91E-005 | |
| MEAN CRITICAL TOTAL TEMP (deg. F) | = | 482. | |
| STANDARD DEVIATION (deg. F) | = | 72.00 | |

LOAD DATA

| | | |
|------------------------|--------|------------|
| TRANSMITTED POWER (HP) | P = | 194.8517 |
| PINION SPEED (rpm) | n(P) = | 1,569.2330 |

DERATING FACTORS

| | | |
|-------------------|------|--------|
| APPLICATION | Ca = | 2.3600 |
| LOAD DISTRIBUTION | Cm = | 1.3000 |
| DYNAMIC | Cv = | 0.9060 |

ANALYSIS OPTIONS

| | | |
|--|---|----|
| NO. OF POINTS ALONG PROFILE CALCULATED | = | 25 |
|--|---|----|

| | | |
|---------------------------|---|------------------|
| DRIVING MEMBER (CODE) | = | GEAR (2) |
| MODIFIED PROFILES? (CODE) | = | MODIFIED (1) |
| COEFF. OF FRICTION OPTION | = | CONSTANT f = .06 |

*****GEOMETRY SUMMARY-1*****

CENTER DISTANCE

STANDARD C(std) = 9.2126
OPERATING C = 9.4094

TRANSVERSE PRESSURE ANGLES

STANDARD (GENERATING) PHI(s) = 20.0000
OPERATING PHI(t) = 23.0690

NORMAL PRESSURE ANGLES

STANDARD (GENERATING) PHI(c) = 20.0000
OPERATING PHI(n) = 23.0690

HELIX ANGLES

STANDARD (GENERATING) PSI(s) = 0.0000
OPERATING PSI = 0.0000
BASE PSI(b) = 0.0000

PITCHES

TRANSVERSE DIAMETRAL Pd = 4.2333
TRANSVERSE CIRCULAR p = 0.7421
NORMAL CIRCULAR pn = 0.7421
TRANSVERSE BASE pb = 0.6974
NORMAL BASE pN = 0.6974
AXIAL px = 0.0000

DISTANCES ALONG LINE OF ACTION

START OF ACTIVE PROFILE (SAP) C1 = 0.5659
LOW SINGLE TOOTH CONTACT (LPSTC) C2 = 0.7981
PITCH POINT C3 = 0.9454
HIGH SINGLE TOOTH CONTACT (HPSTC) C4 = 1.2632
END OF ACTIVE PROFILE (EAP) C5 = 1.4955
DISTANCE BETWEEN INTERFERENCE POINTS C6 = 3.6870
ACTIVE LENGTH OF LINE OF ACTION Z = 0.9296
PINION ADDENDUM PORTION OF Z Za = 0.5501
PINION DEDENDUM PORTION OF Z Zb = 0.3795

LENGTH OF CONTACT LINE

MINIMUM Lmin = 3.1496
MAXIMUM Lmax = 6.2992
AVERAGE Lavg = 4.7244

GEARTECH
CASE IDENT: WTC HS/SP
SCORING+ v.1.03A

ANALYST: RLE

DATE: 06-14-02

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*****GEOMETRY SUMMARY-2*****

RATIOS

| | | |
|------------------------------|-------|--------|
| CONTACT LENGTH | mL = | 2.0000 |
| TRANSVERSE (PROFILE) CONTACT | mp = | 1.3330 |
| AXIAL (FACE) CONTACT | mF = | 0.0000 |
| TOTAL CONTACT | mt = | 1.3330 |
| GEAR | mG = | 2.9000 |
| LOAD SHARING | mN = | 1.0000 |
| LOAD SHARING | mNa = | 1.0000 |

DIAMETERS

| | | PINION | GEAR |
|------------------|---------|--------|---------|
| POINTED TEETH | dp,Dp = | 5.5669 | 14.6942 |
| OPERATING PITCH | d,D = | 4.8254 | 13.9935 |
| GENERATING PITCH | ds,Ds = | 4.7244 | 13.7008 |
| LIMIT (SAP) | dc,Dc = | 4.5815 | 13.6002 |
| TOP OF FILLET | de,De = | 4.4982 | 13.4184 |
| BASE | db,Db = | 4.4395 | 12.8745 |
| ROOT | dR,DR = | 4.2634 | 13.2352 |

TOOTH DEPTHS

| | | | |
|---------------------|-----------|--------|--------|
| OPERATING ADDENDA | a1,a2 = | 0.2638 | 0.1572 |
| OPERATING DEDENDA | b1,b2 = | 0.2810 | 0.3791 |
| OPERATING CLEARANCE | c1,c2 = | 0.1153 | 0.1237 |
| WHOLE DEPTH | ht1,ht2 = | 0.5448 | 0.5364 |
| WORKING DEPTH | hK = | 0.4211 | |

TRANSVERSE CIRCULAR TOOTH THICKNESSES

| | | | |
|------------|-----------|--------|--------|
| TOPLAND | tol,to2 = | 0.1501 | 0.1974 |
| OPERATING | tr1,tr2 = | 0.4131 | 0.3348 |
| GENERATING | tg1,tg2 = | 0.4440 | 0.4423 |
| BASE | tbl,tb2 = | 0.4834 | 0.6075 |

NORMAL CIRCULAR TOOTH THICKNESSES

| | | | |
|------------|-------------|--------|--------|
| TOPLAND | tno1,tno2 = | 0.1501 | 0.1974 |
| OPERATING | tnr1,tnr2 = | 0.4131 | 0.3348 |
| GENERATING | tng1,tng2 = | 0.4440 | 0.4423 |
| BASE | tnb1,tnb2 = | 0.4834 | 0.6075 |

| | | | |
|------|---------|--------|--------|
| LEAD | L1,L2 = | 0.0000 | 0.0000 |
|------|---------|--------|--------|

OPERATING CIRCULAR BACKLASH

| | | |
|------------|------|--------|
| TRANSVERSE | B = | 0.0101 |
| NORMAL | Bn = | 0.0101 |

NOTE: All dims in inches, all angles in degrees.

GEARTECH

ANALYST: RLE

DATE: 06-14-02

=====
LOAD/DERATING FACTOR SUMMARY
=====

NOMINAL OPERATING LOADS

| | | |
|-------------------------|------------|-----------|
| PINION TORQUE (lb.-in.) | T1 = | 7.83E+003 |
| TANGENTIAL LOAD (lb.) | (Wtr)nom = | 3.24E+003 |

COMBINED DERATING FACTOR

| | | |
|-------------------|--------|--------|
| C(D) = Ca Cm / Cv | C(D) = | 3.3863 |
|-------------------|--------|--------|

ACTUAL OPERATING LOADS (includes C(D))

| | | |
|---------------------------|-------|-----------|
| TANGENTIAL LOAD (lb.) | Wtr = | 1.10E+004 |
| NORMAL LOAD (lb.) | WNr = | 1.19E+004 |
| NORMAL UNIT LOAD (lb/in.) | wNr = | 3.79E+003 |

=====
MATERIALS/LUBE DATA SUMMARY
=====

MATERIAL DATA

| | | |
|--|-------|------------|
| REDUCED MODULUS (lb./in ²) | E' = | 3.30E+007 |
| EHD MATERIAL PARAMETER | G = | 3,267.0330 |
| COMPOSITE SURFACE ROUGHNESS (micro-in) rms | rms = | 28.2843 |
| AVERAGE SURFACE ROUGHNESS (micro-in) rms | rms = | 20.0000 |

LUBRICANT DATA

| | | |
|--|----------|-------------|
| LUBRICANT TYPE (CODE) | = | MINERAL (2) |
| ABSOLUTE VISCOSITY (cP) | ETA(o) = | 1.05E+001 |
| ABSOLUTE VISCOSITY (reyns) | MU(o) = | 1.52E-006 |
| PRESSURE-VISCOSITY COEFF. (lb ² /in.) | ALPHA = | 9.91E-005 |
| GEAR BULK TEMPERATURE (deg. F) | Tb = | 185.0000 |

=====
RATING SUMMARY
=====

| | | |
|---|----------|------------|
| PITCHLINE VELOCITY (ft/min.) | Vtr = | 1,982.3788 |
| APPROACH ACTION (%) | = | 59.17% |
| RECESS ACTION (%) | = | 40.83% |
| MAXIMUM SPECIFIC SLIDING RATIO | Vss = | -0.9789 |
| MAXIMUM SLOPE | = | 8.8132 |
| MAXIMUM HERTZIAN STRESS (lb/in ²) | qo = | 178,337. |
| MAXIMUM TOTAL CONJUNCTION TEMP. (deg. F) | Tc = | 310. |
| MINIMUM FILM THICKNESS (micro-in) | hmin = | 8.4 |
| MINIMUM SPECIFIC FILM THICKNESS | LAMBDA = | 0.297 |
| PROBABILITY OF SCORING (%) | Ps = | < 5% |
| PROBABILITY OF WEAR (%) | Pw = | 87% |

*****Vss, hmin, Tc, etc. AT 5 REFERENCE POINTS*****

| | Roll Angle (deg) | Rolling Velocity (in/s) | | Sliding Velocity (in/s) | | Entraining Velocity (in/s) | Specific Sliding Ratio | |
|----|------------------|-------------------------|--------|-------------------------|---------|----------------------------|------------------------|---------|
| | | Vr1 | Vr2 | Vs1 | Vs2 | | Ve | Vss1 |
| 1. | 14.61 | 92.99 | 176.86 | -83.87 | 83.87 | 269.85 | -0.9019 | 0.4742 |
| 2. | 20.60 | 131.15 | 163.70 | -32.55 | 32.55 | 294.85 | -0.2482 | 0.1988 |
| 3. | 24.40 | 155.35 | 155.35 | 0.00 | 0.00 | 310.71 | 0.0000 | 0.0000 |
| 4. | 32.61 | 207.59 | 137.34 | 70.24 | -70.24 | 344.93 | 0.3384 | -0.5114 |
| 5. | 38.60 | 245.75 | 124.18 | 121.56 | -121.56 | 369.93 | 0.4947 | -0.9789 |

| | Roll Angle (deg) | Hertzian Stress (lb/in ²) | Friction Coeff. | Flash T. Rise (deg F) | Total Temp (deg F) | EHD Film Thk (micro-in) | Specific Film Thk |
|----|------------------|---------------------------------------|-----------------|-----------------------|--------------------|-------------------------|-------------------|
| | | | | | | | |
| 1. | 14.61 | 77,026 | 0.060 | 45 | 230 | 9.2 | 0.324 |
| 2. | 20.60 | 178,337 | 0.060 | 67 | 252 | 8.5 | 0.300 |
| 3. | 24.40 | 168,201 | 0.060 | 0 | 185 | 9.3 | 0.327 |
| 4. | 32.61 | 154,757 | 0.060 | 125 | 310 | 10.7 | 0.378 |
| 5. | 38.60 | 0 | 0.060 | 0 | 185 | 0.0 | 0.000 |

| | Roll Angle (deg) | -----Profile Radii of Curvature (inches)----- | | | | |
|---------|------------------|---|--------|--------|--------|-----------------|
| | | Transverse | | Normal | | Normal Relative |
| epsilon | | rho1 | rho2 | rhon1 | rhon2 | rhon |
| 1. | 14.61 | 0.5659 | 3.1211 | 0.5659 | 3.1211 | 0.4790 |
| 2. | 20.60 | 0.7981 | 2.8889 | 0.7981 | 2.8889 | 0.6253 |
| 3. | 24.40 | 0.9454 | 2.7416 | 0.9454 | 2.7416 | 0.7030 |
| 4. | 32.61 | 1.2632 | 2.4238 | 1.2632 | 2.4238 | 0.8304 |
| 5. | 38.60 | 1.4955 | 2.1915 | 1.4955 | 2.1915 | 0.8889 |

- 1. = SAP: Start of Active Profile
- 2. = LPSTC: Lowest Point of Single Tooth Contact
- 3. = P: Pitch point
- 4. = HPSTC: Highest Point of Single Tooth Contact
- 5. = EAP: End of Active Profile

Appendix C
Bearing Rating

Bearing Fatigue L10aa and L1aa Life

L10aa and L1aa life are calculated using the SKF [5] new life method for adjusted rating life where:

$$L_{naa} = a_1 * a_{SKF} * L_{10}$$

$$L_{10} = (16667/n) * (C/P)^p \quad (p = 10/3 \text{ for roller bearings})$$

L_{10aa} = adjusted rating life according to new life theory for 10% probability of failure (hours)

L_{1aa} = adjusted rating life according to new life theory for 1% probability of failure (hours)

$a_1 = 1.0$ (for 10% failure probability)

$a_1 = 0.21$ (for 1% failure probability)

a_{SKF} = life adjustment factor based on new life theory (from Diagram 5 [5] as a function of viscosity ratio κ and $\eta_c * P_u/P$)

$\kappa = v/v_1$ (viscosity ratio)

v = actual viscosity at operating temperature (mm²/s)

v_1 = viscosity required for adequate lubrication (mm²/s)

$\eta_c = 0.5$ (contamination factor for normal conditions)

n = speed (rpm)

C = Basic dynamic capacity (N)

P_u = Fatigue load limit (N)

P = Equivalent dynamic load at effective power of 430.43 kW (N)

LS planet bearings

$$W = T/(a*Q) = 160,654/(0.304*3) = 176,156 \text{ N} \quad (\text{load based on rated torque})$$

$$W = (430.43/500)(176,156) = 151,644 \text{ N} \quad (\text{equivalent load})$$

$$n = \omega_{pr} = \omega_c(z_3/z_2) = 29.72(115/49) = 69.751 \text{ rpm}$$

$$L_{10} = (16667/n)(C/P)^{10/3} = (16667/69.751)(1,070,000/151,644)^{10/3} = 161,000 \text{ hours}$$

$$d_m = (d+D)/2 = (170 + 280)/2 = 225 \text{ mm}$$

$$v_1 = 85 \text{ mm}^2/\text{s} \quad (\text{from diagram 1 [5] for } d_m = 225, n = 70 \text{ rpm})$$

$$v = 13.5 \text{ mm}^2/\text{s} \quad (\text{from Mobil ASTM Chart at } 85^\circ\text{C})$$

$$\kappa = v_1/v = 13.5/85 = 0.16$$

$$\eta_c = 0.5 \quad (\text{assuming normal conditions})$$

$$P_u/P = 170,000/151644 = 1.121$$

$$\eta_c(P_u/P) = 0.5(1.121) = 0.56$$

$$a_{SKF} = 0.14 \quad (\text{from diagram 5 [5] for } \eta_c(P_u/P) = 0.56 \text{ and } \kappa = 0.16)$$

$$L_{10aa} = a_1*a_{SKF}*L_{10} = 1.0(0.14)(161,000) = 22,540 \text{ hours}$$

$$L_{1aa} = a_1*a_{SKF}*L_{10} = 0.21(0.14)(161,000) = 4,733 \text{ hours}$$

HS planet bearings

$$W = T/(a*Q) = 20,690/(0.239*3) = 28,857 \text{ N} \quad (\text{load based on rated torque})$$

$$W = (430.43/500)(28,857) = 24,842 \text{ N} \quad (\text{equivalent load})$$

$$n = \omega_{pr} = \omega_c(z_3/z_2) = 230.767(136/58) = 541.109 \text{ rpm}$$

$$L_{10} = (16667/n)(C/P)^{10/3} = (16667/541.109)(345,000/24,842)^{10/3} = 198,311 \text{ hours}$$

$$d_m = (d+D)/2 = (70 + 150)/2 = 110 \text{ mm}$$

$$v_1 = 24 \text{ mm}^2/\text{s} \quad (\text{from diagram 1 [5] for } d_m = 110, n = 541 \text{ rpm})$$

$$v = 13.5 \text{ mm}^2/\text{s} \quad (\text{from Mobil ASTM Chart at } 85^\circ\text{C})$$

$$\kappa = v_1/v = 13.5/24 = 0.56$$

$$\eta_c = 0.5 \quad (\text{assuming normal conditions})$$

$$P_u/P = 45,000/24,842 = 1.81$$

$$\eta_c(P_u/P) = 0.5(1.81) = 0.91$$

$$a_{SKF} = 0.8 \quad (\text{from diagram 5 [5] for } \eta_c(P_u/P) = 0.91 \text{ and } \kappa = 0.56)$$

$$L_{10aa} = a_1*a_{SKF}*L_{10} = 1.0(0.8)(198,311) = 158,600 \text{ hours}$$

$$L_{1aa} = a_1*a_{SKF}*L_{10} = 0.21(0.8)(198,311) = 33,316 \text{ hours}$$